

Cross-scale and cross-interface processes and Arctic Amplification

Patrick C. Taylor

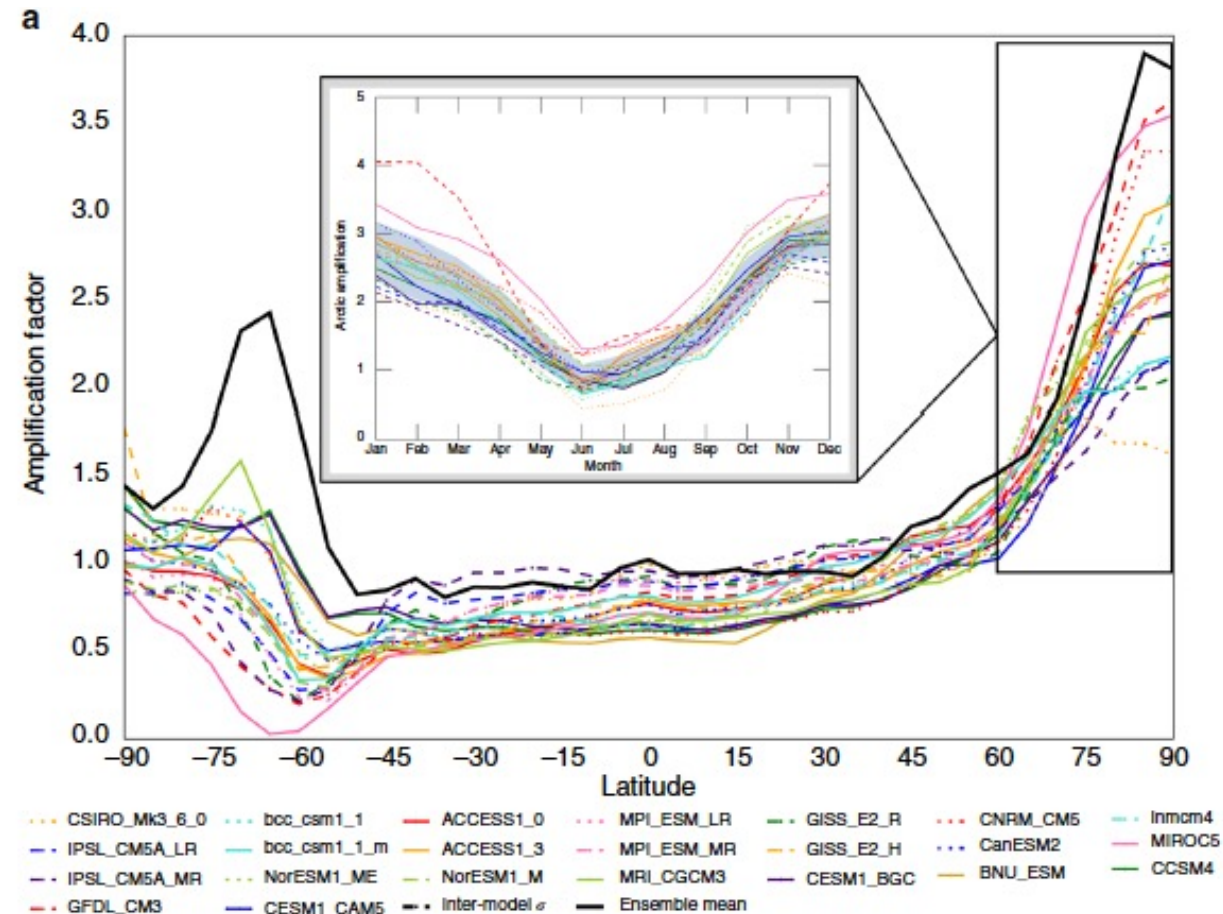
NASA Langley Research Center

April 18, 2023

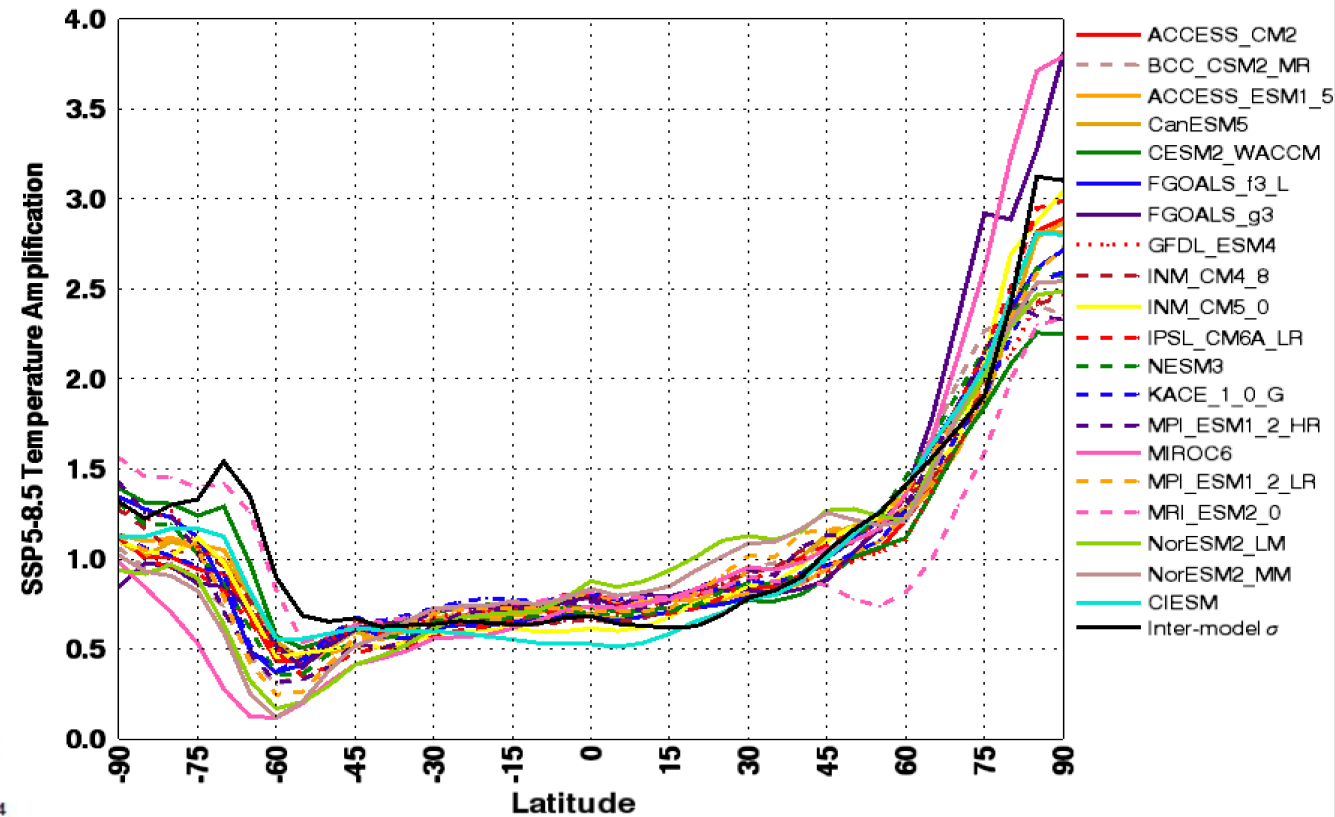
Acknowledgements: Robyn C. Boeke, Linette N. Boisvert, Nicole Feldl, Matthew Henry, Yiyi Huang, Peter L. Langen, Wei Liu , Felix Pithan, Sergio A. Sejas, Ivy Tan, Melinda Webster

Substantial uncertainty in Arctic climate projections

CMIP5 (RCP8.5)



CMIP6 (SSP8.5)



The inter-model spread in projected Arctic Amplification remains unchanged between CMIP5 and CMIP6.

The Arctic Amplification (AA) Concept: Arrhenius (1896)

THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

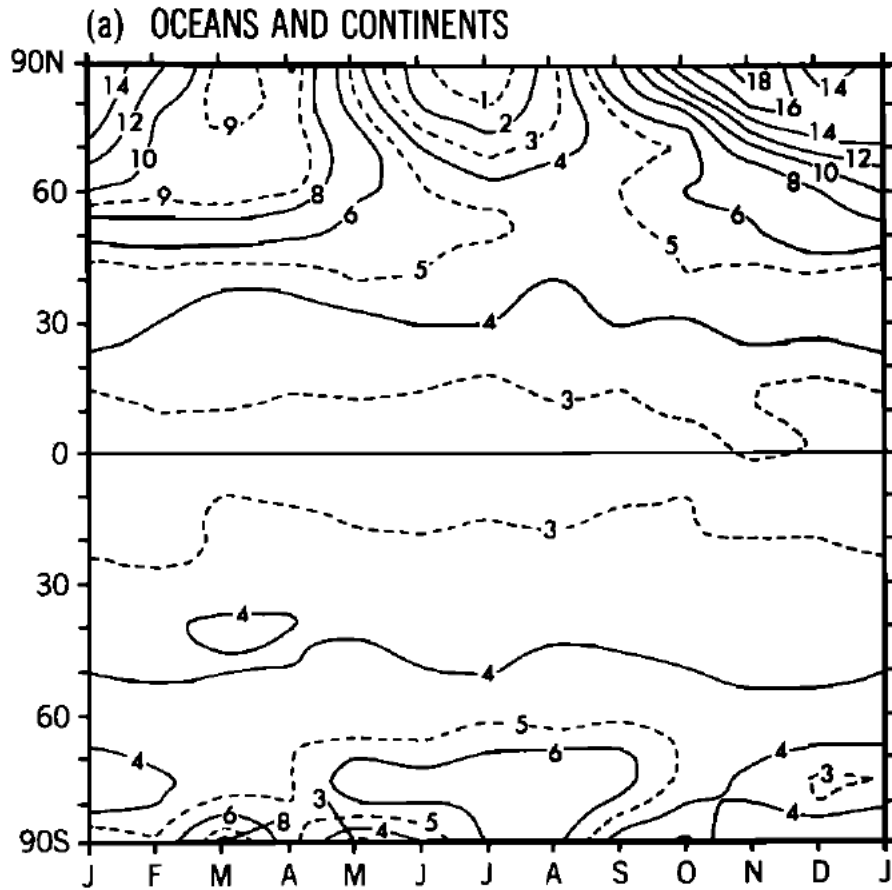
[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS *.

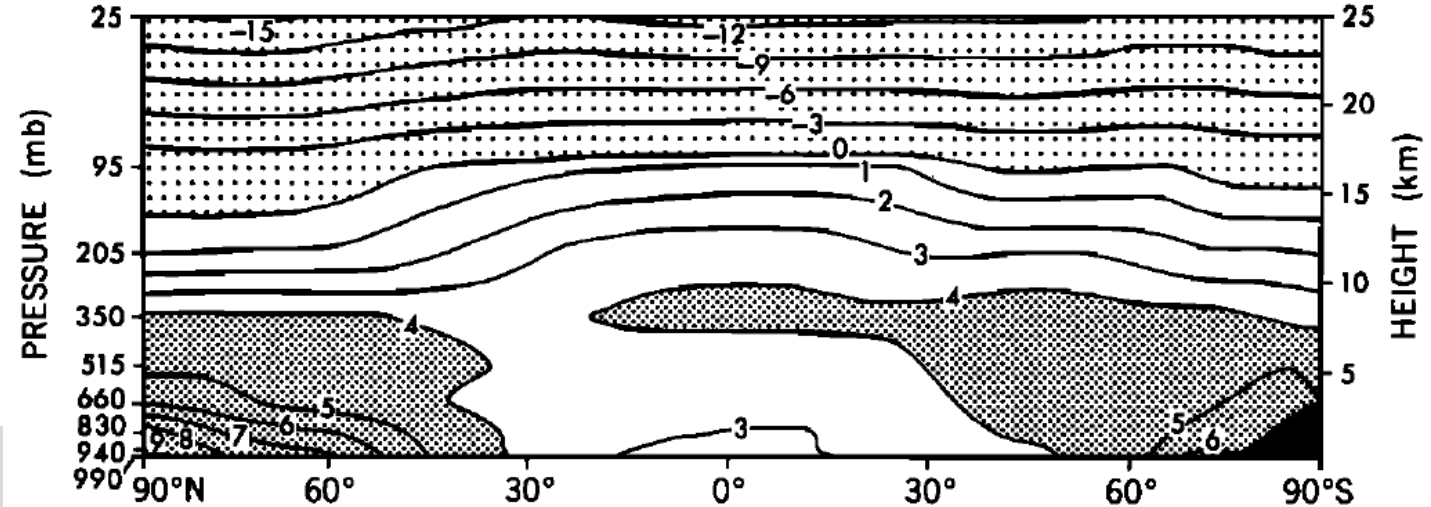
- Arrhenius (1896) provided one of the earliest descriptions of Arctic Amplification.
- Origins of AA came within the context of explaining glacial/inter-glacial periods.
- **Key Mechanism:** Surface albedo changes due to the north-south progression of the snow-ice line.
- Energy balance calculations demonstrated the impact of surface albedo.

What is Arctic Amplification?



Larger Arctic Warming concentrated in fall and winter and near the surface.

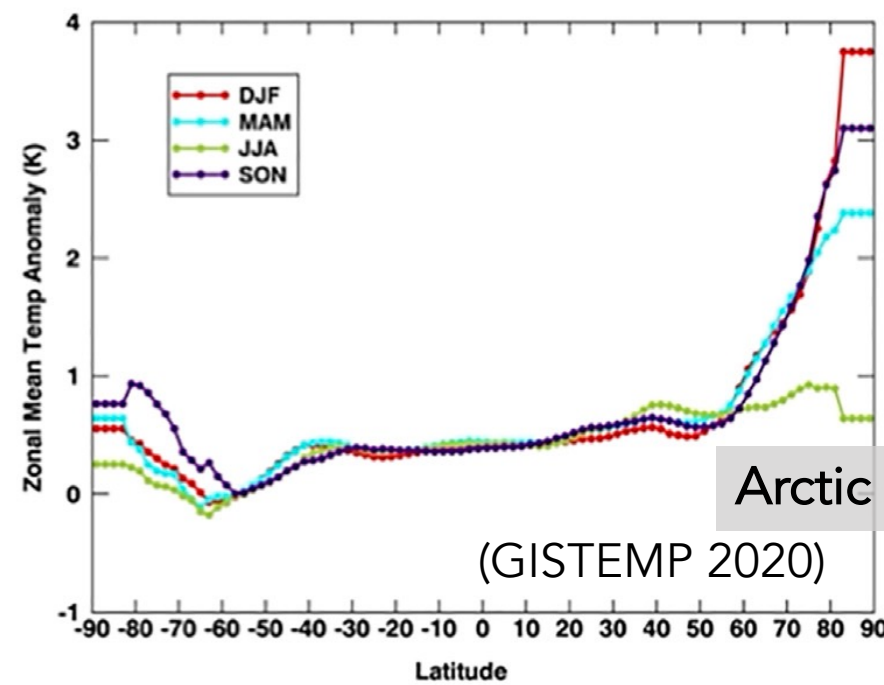
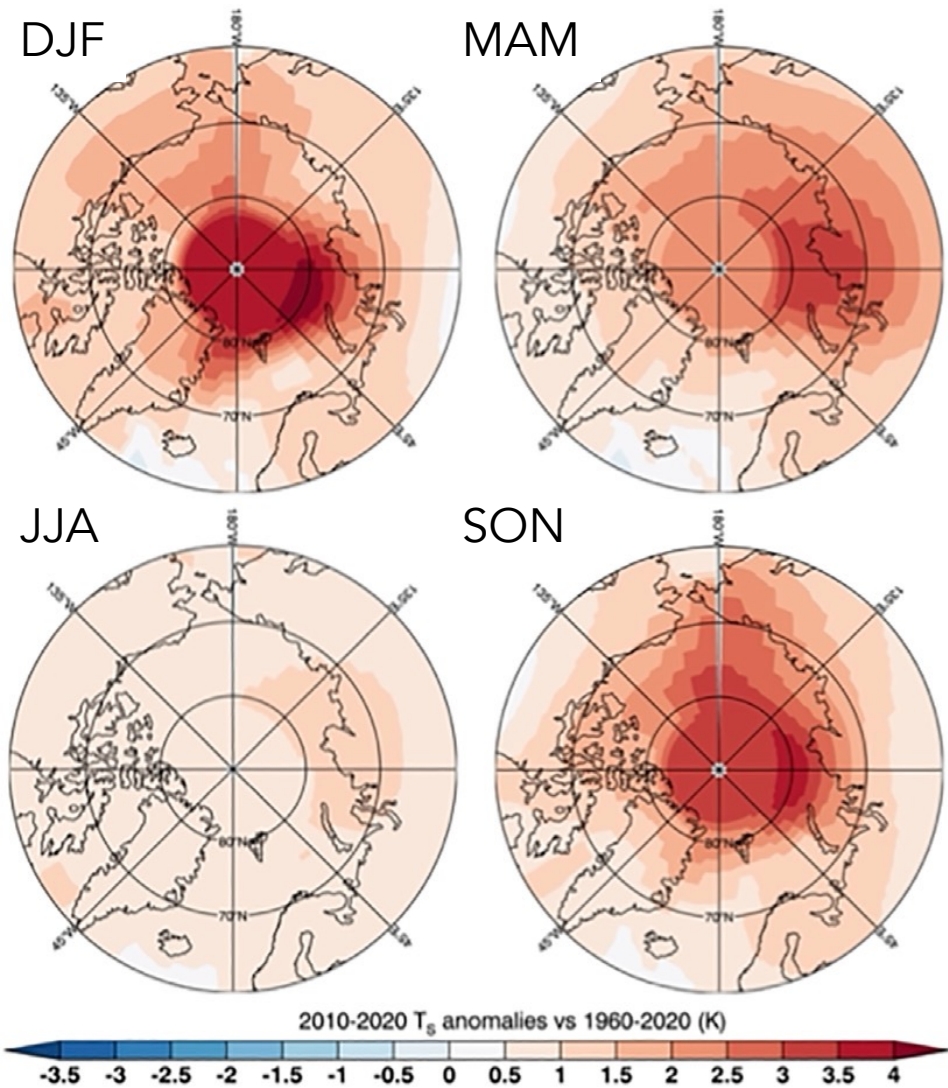
Arctic Amplification is the phenomenon where the Arctic is more sensitive to a climate perturbation than the global average.



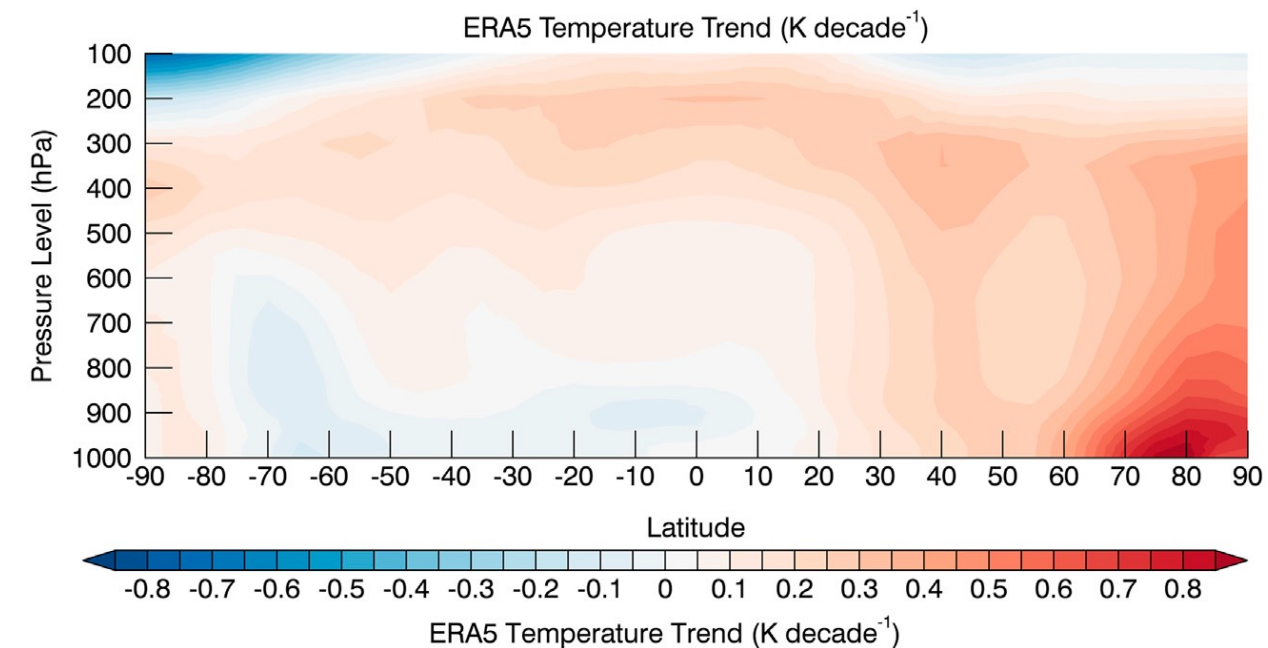
Arctic

Antarctic

Manabe and Stouffer (1980)

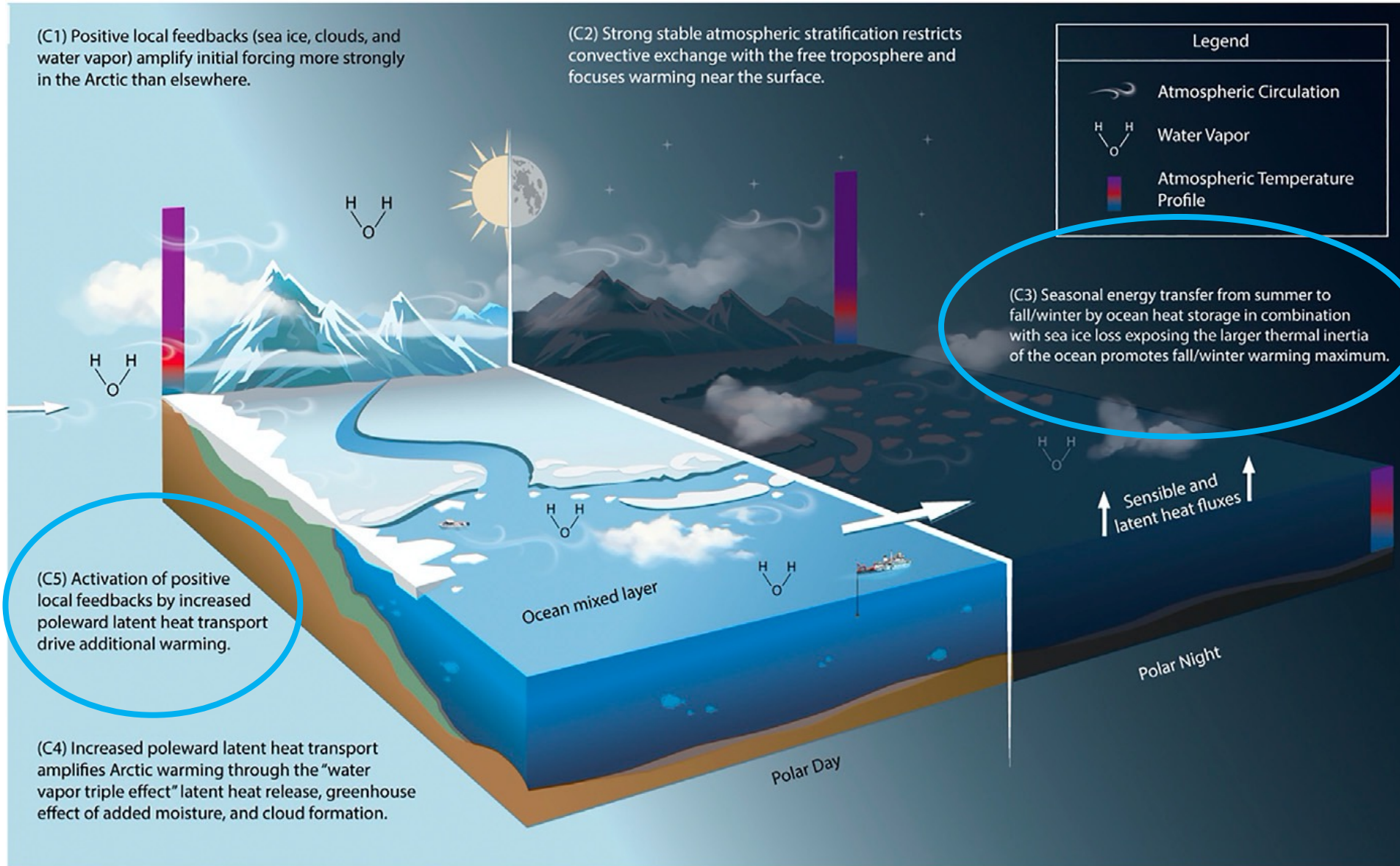


Observations show the fall/winter maximum and the surface-based profile of warming.



Features of AA:
Observational Evidence

Conceptual model of Arctic Amplification

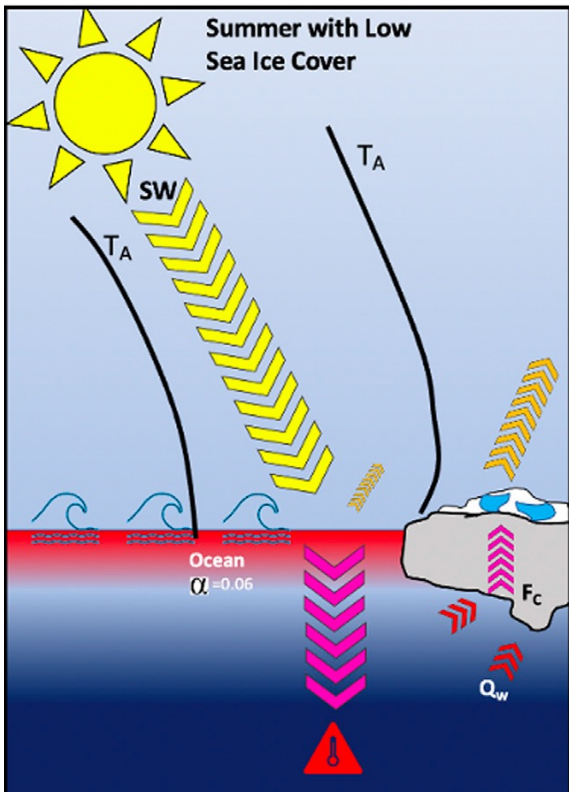


While improved understanding of individual process is critical, our conceptual model highlights the need to account for local feedback and remote process interactions within the context of the annual cycle to be able to constrain the high-end of model projections.

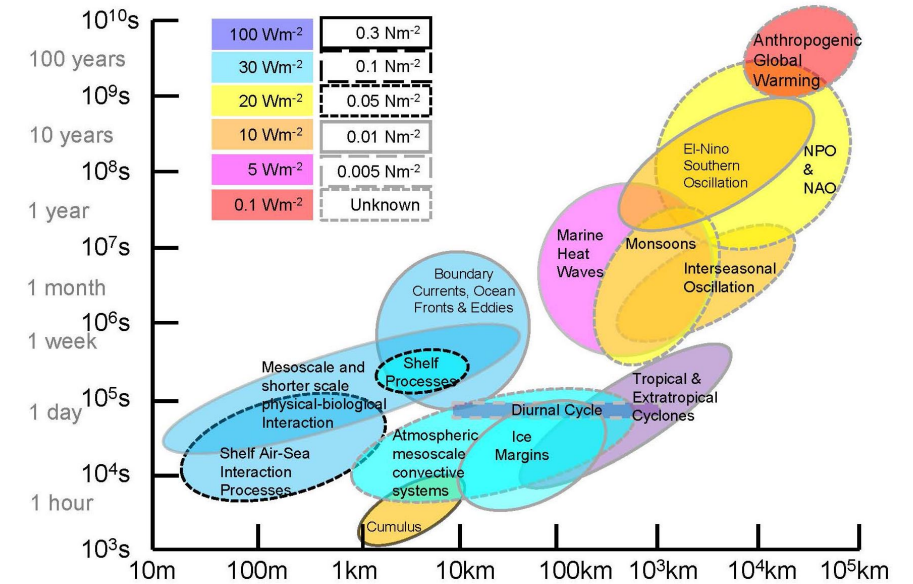
Taylor et al. (2022)

Cross-scale interactions defined...

Cross-scale interactions refer to processes at one spatial or temporal scale interacting with processes at another scale that can result in nonlinear dynamics with thresholds.



Flux Accuracies and Processes

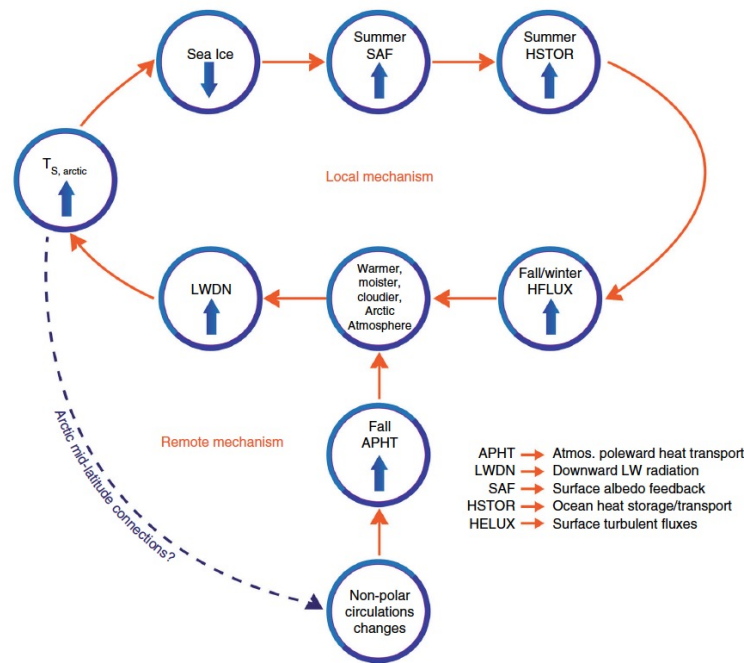


Cross-interface processes defined...

Cross-interface processes refer to processes that result in the exchange of mass, energy, or momentum from one climate sub-component to another (e.g., atmosphere-ocean and sea ice-ocean coupling)

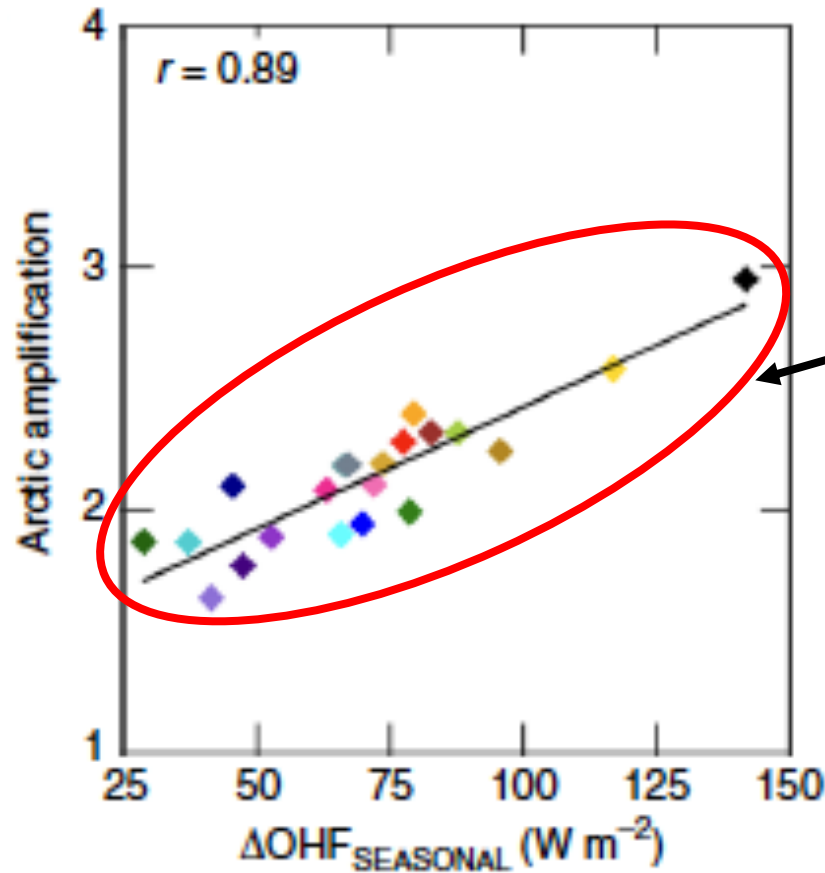
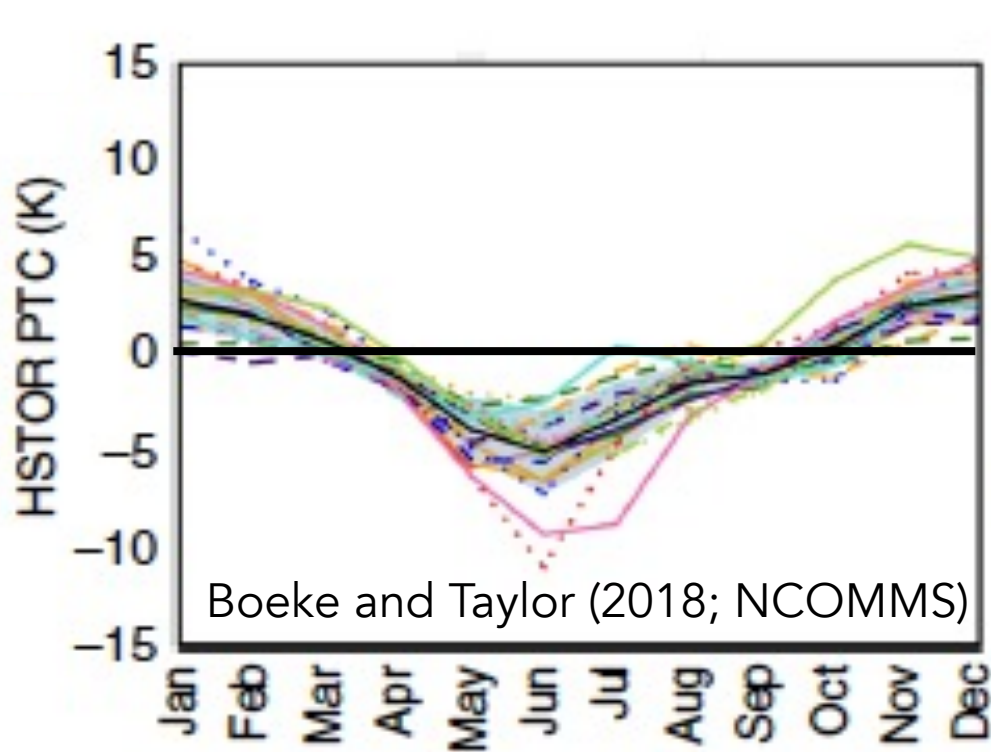
Influence of seasonal time scale energy transfer to climate change time scale:

Interactions of the upper Arctic Ocean, sea ice, and atmosphere



Refine a pictural representation of the process

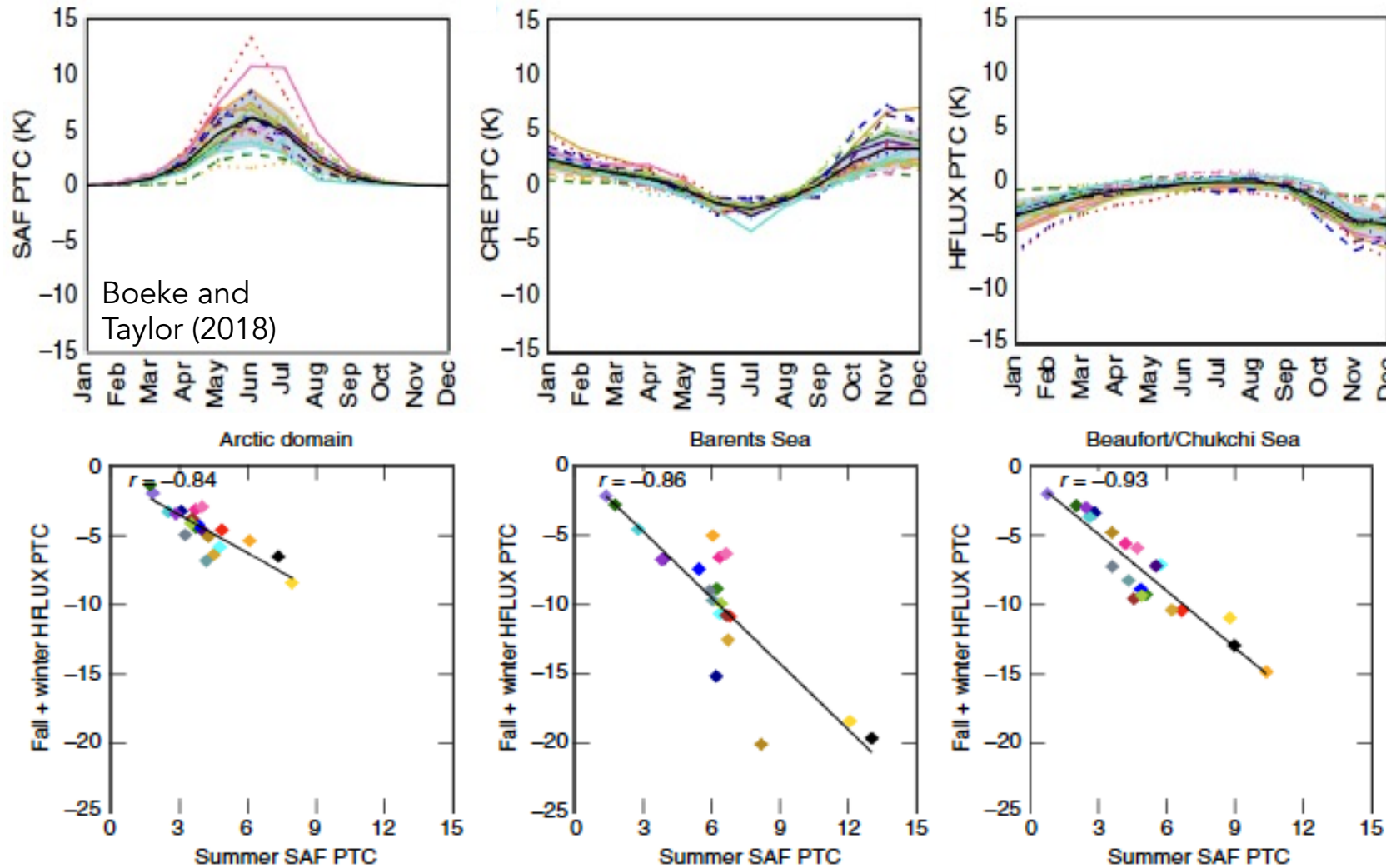
Greater seasonal energy transfer, greater Arctic Amplification



Models with a greater **change in the seasonal amplitude of ocean heat storage** produce **greater Arctic Amplification**.

The seasonal transfer of energy from summer to fall has a fingerprint on the centennial scale Arctic Amplification.

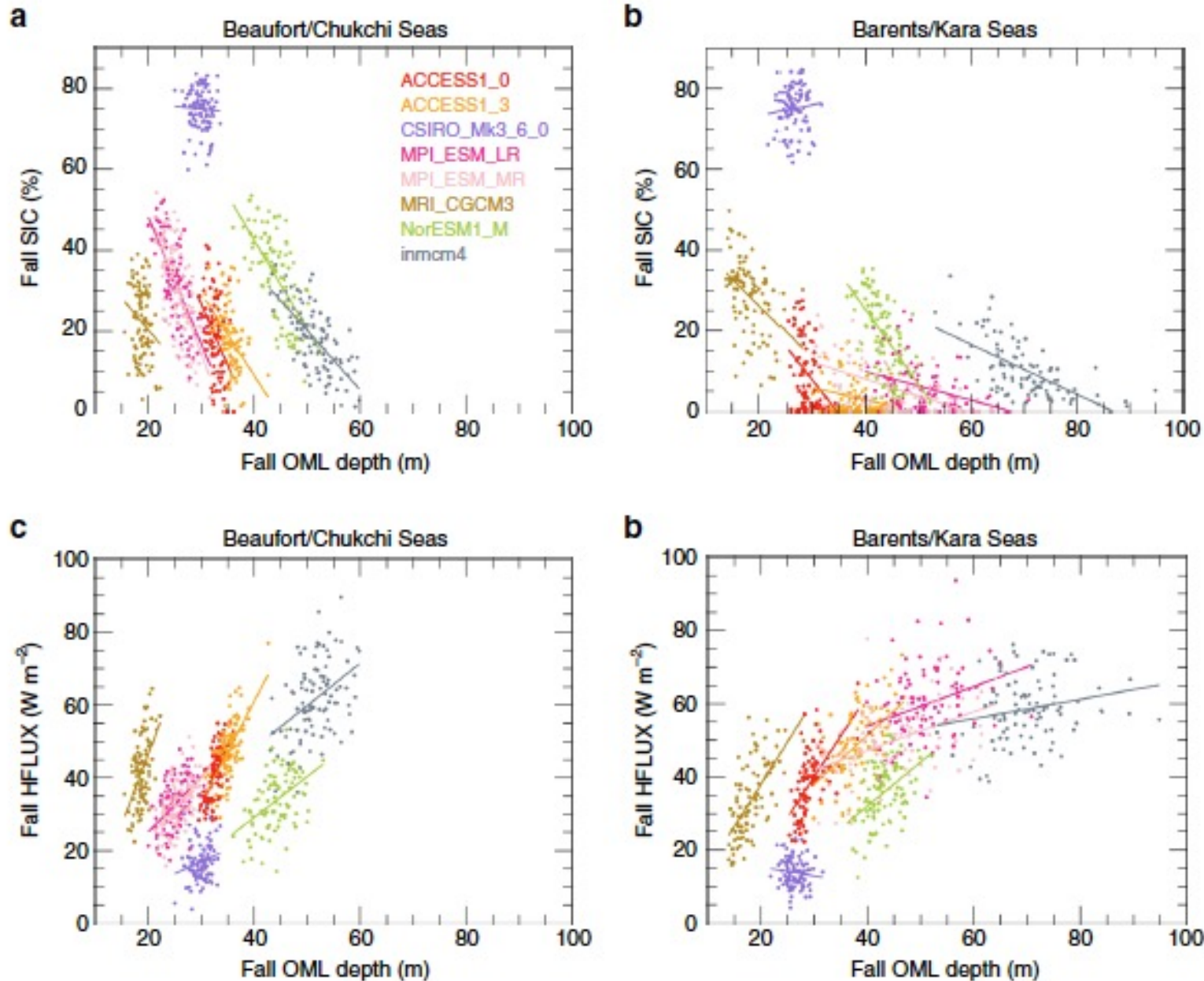
Processes driving the change in seasonal energy transfer



The seasonal transfer of energy results from the summer surface albedo feedback and fall/winter increase in surface-to-atmosphere surface turbulent fluxes.

Cross-scale interactions due to seasonal energy transfer are tied to cross-interface energy exchanges.

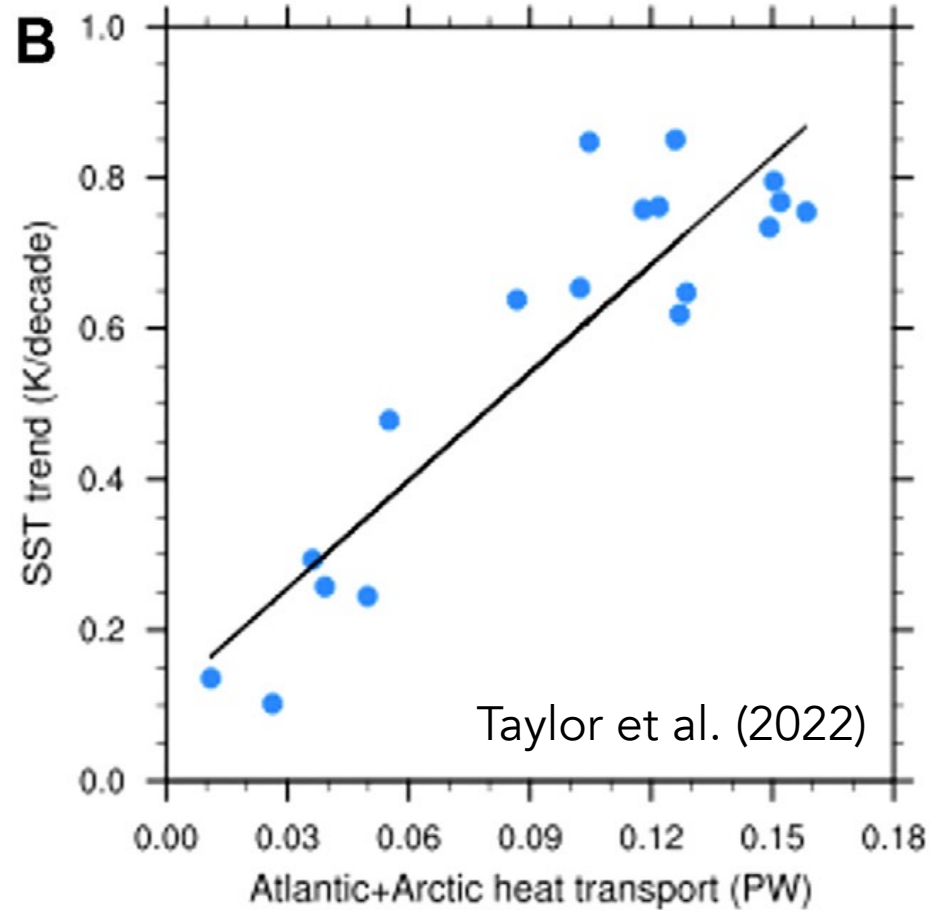
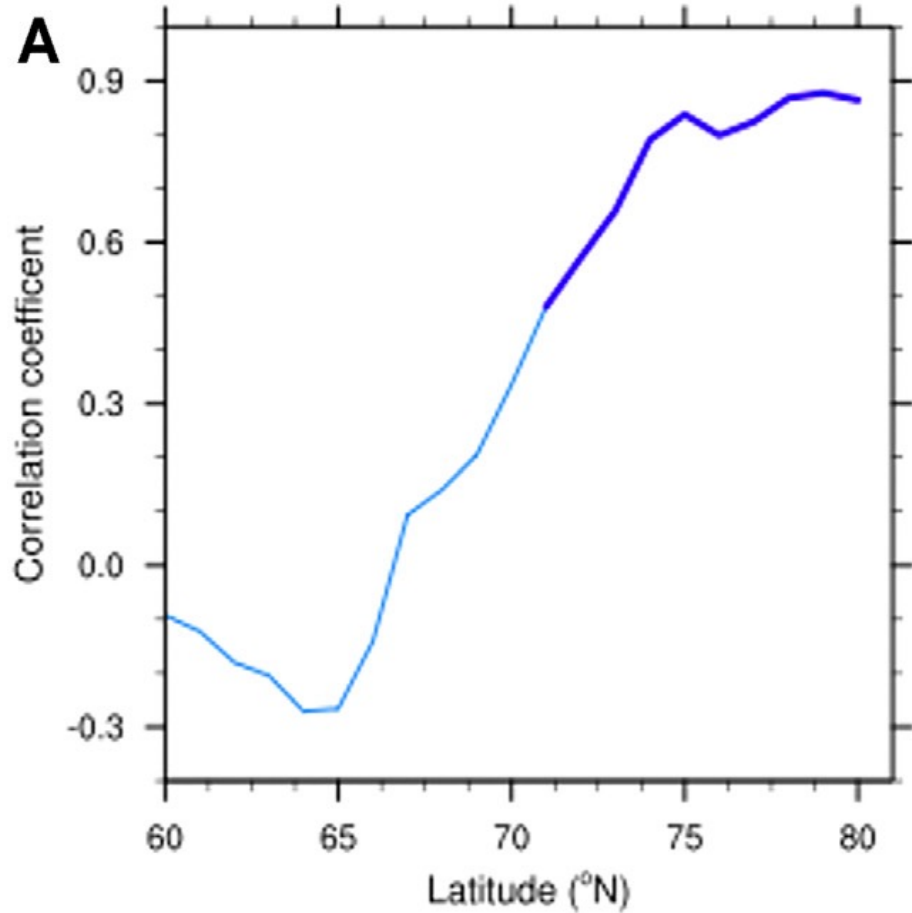
Seasonal energy transfer: Ocean Mixed Layer Depth Uncertainty



Ocean mixed layer depth and processes modulates the seasonal exchange of energy between the ocean, sea ice, and atmosphere.

Stark inter-model differences are found between the Arctic Ocean mixed depths and the correlations with sea ice and turbulent fluxes.

Seasonal energy transfer: Influence of Ocean heat transport



OHT into the Arctic from the Atlantic correlates with projected Arctic warming, such that larger transport increases yields larger warming

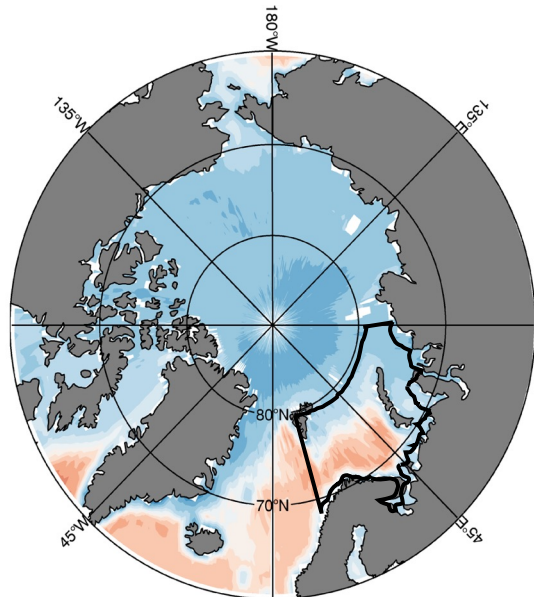
Ocean heat transports may also play a key role in delaying sea ice freeze-up and enhancing surface turbulent fluxes in fall/winter.

Seasonal energy transfer: Surface turbulent flux uncertainty

Satellite observations => central Arctic is a **heat sink** to the Arctic atmosphere in winter

CMIP6 models => central Arctic is a **heat source** to the Arctic atmosphere in winter

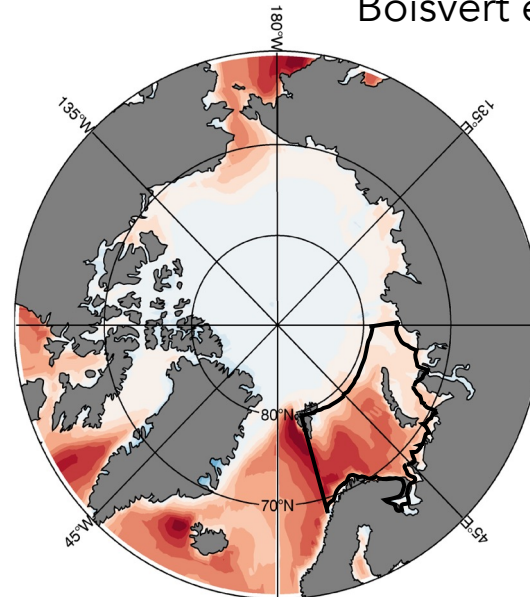
AIRS SHF



AIRS ONDJ SHF (W m^{-2})



CMIP6 SHF

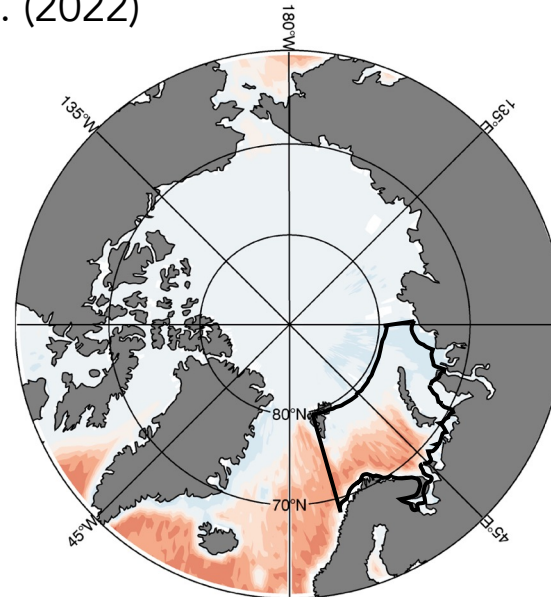


CMIP6 ONDJ SHF (W m^{-2})



Boisvert et al. (2022)

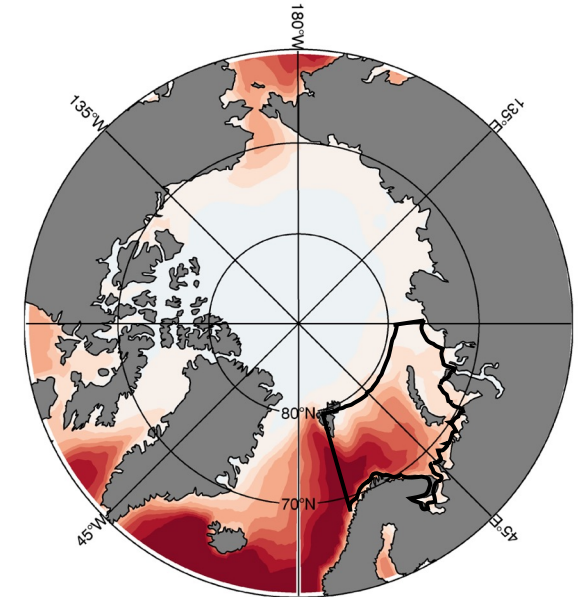
AIRS LHF



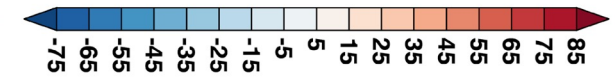
AIRS ONDJ LHF (W m^{-2})



CMIP6 LHF



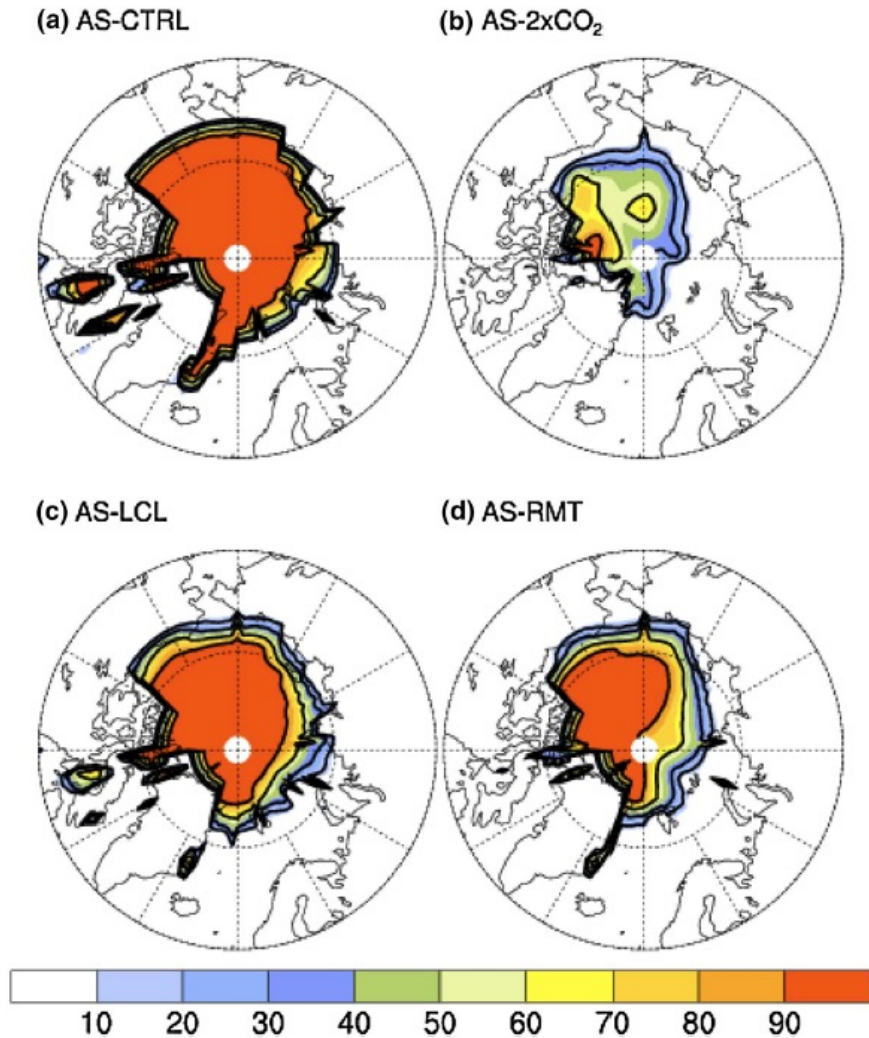
CMIP6 ONDJ LHF (W m^{-2})



Key uncertainties remain in the parameterization of surface turbulent fluxes in climate models.

Remote process and local feedback interactions:

Rectification of the synoptic scale onto the climate scale



Sea ice concentration

Model simulations that account for **only local feedbacks** (AS-LCL) or **only remote processes** (AS-RMT) show less sea ice loss than when local and remote processes are both active (**AS-2xCO₂**)

The amplification of remote warming by local feedbacks may be key to producing large Arctic Amplification.

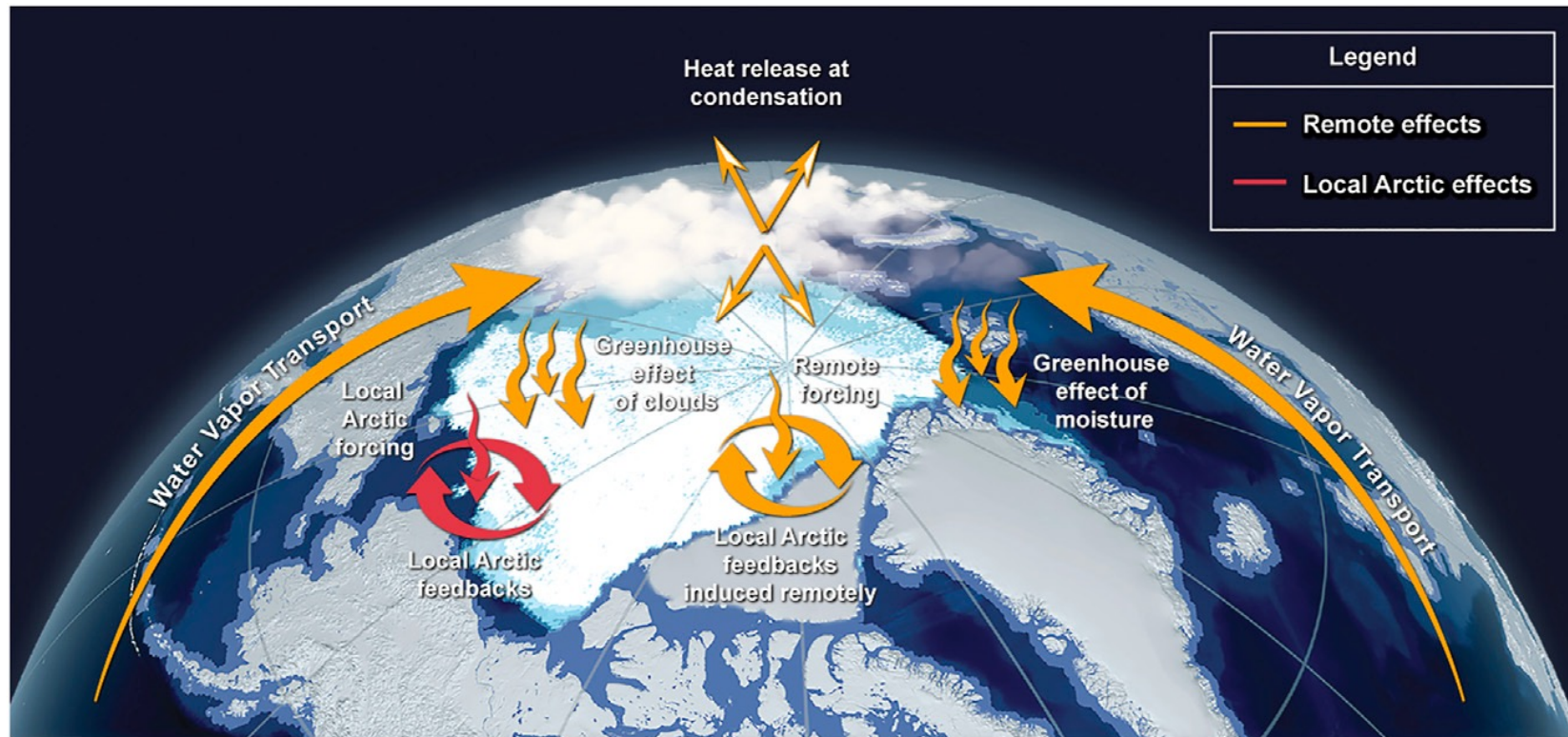
Remote process and local feedback interactions:

Rectification of the synoptic scale onto the climate scale

Key Concepts:

1. The Arctic shows a different sensitivity to changes in poleward moisture transport than to dry static energy transport.
2. The amount of surface warming and SEB perturbation to poleward heat transfer is sensitive to the vertical structure of the transfer.

Sensitivity to moisture vs. dry static energy transport: "Water Vapor Triple Effect"

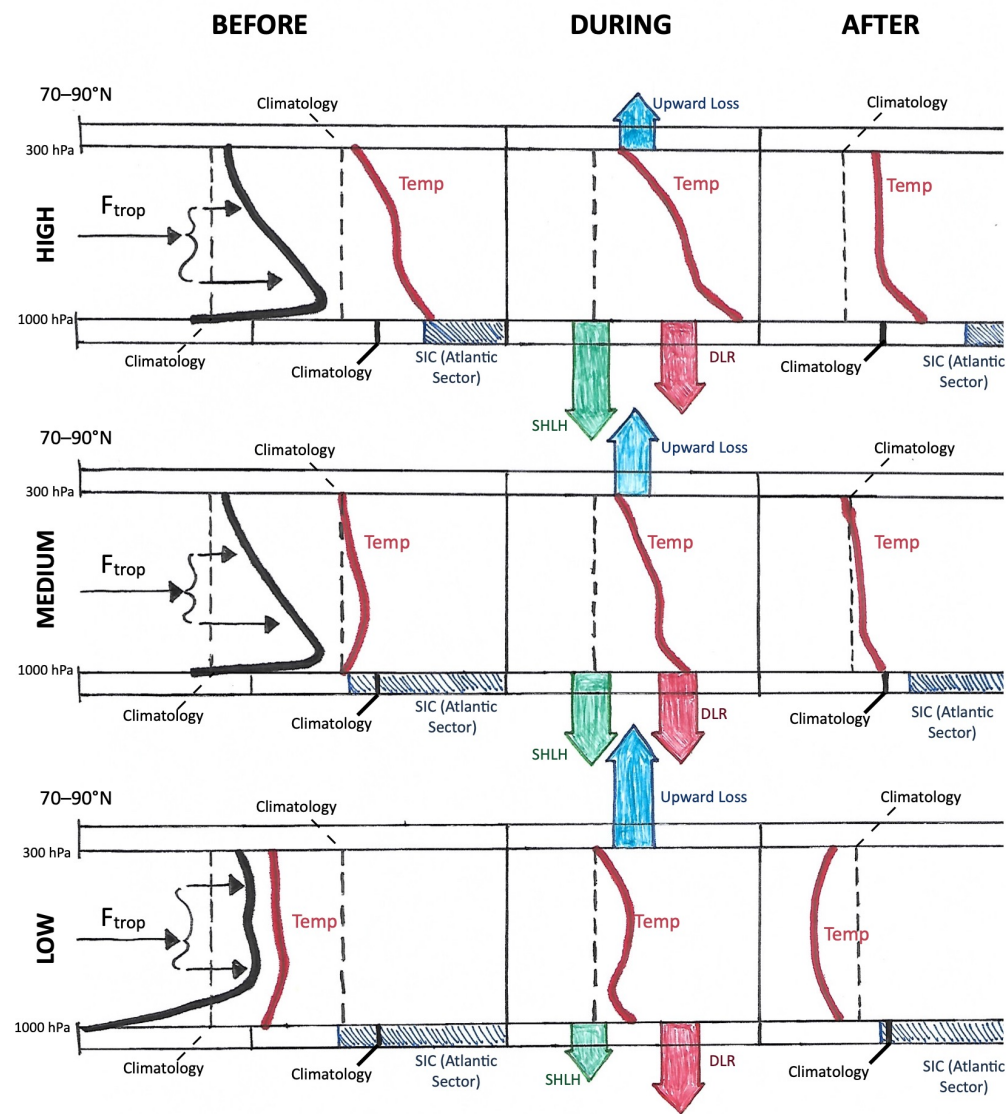


- **Water Vapor Triple Effect:** the multiple influences of water vapor on the Arctic energy budget from condensation and greenhouse effects of moisture and clouds.
- Graversen and Burtu (2016) found an order of magnitude larger warming per unit of energy due to the Arctic LH transport than DSE, due to the accompanying changes in specific humidity and clouds.

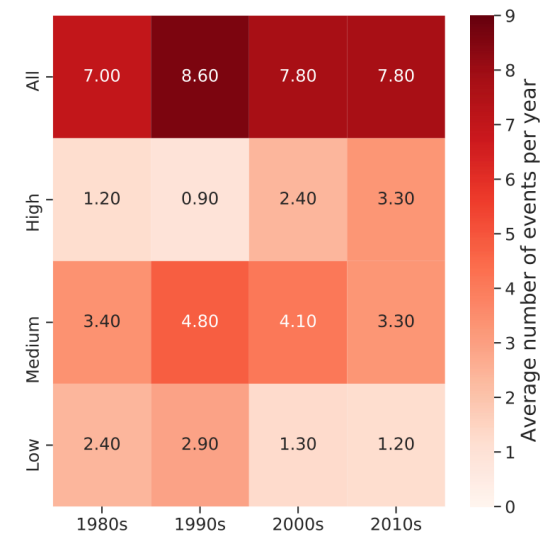
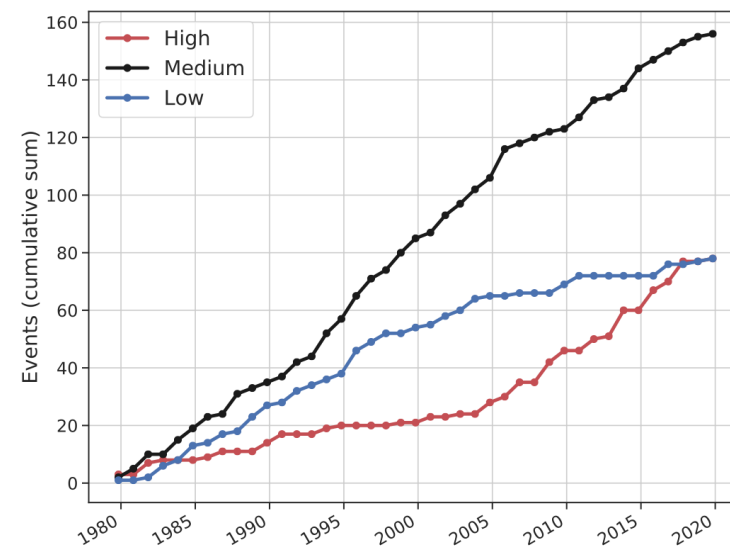
The Arctic surface is more sensitive to a change in poleward moisture transport than a change in dry static energy transport.

Sensitivity of surface heating by synoptic scale heat transport events to vertical structure

High efficiency surface warming events exhibit greater moist static energy transport in lower troposphere and occur under lower sea ice.



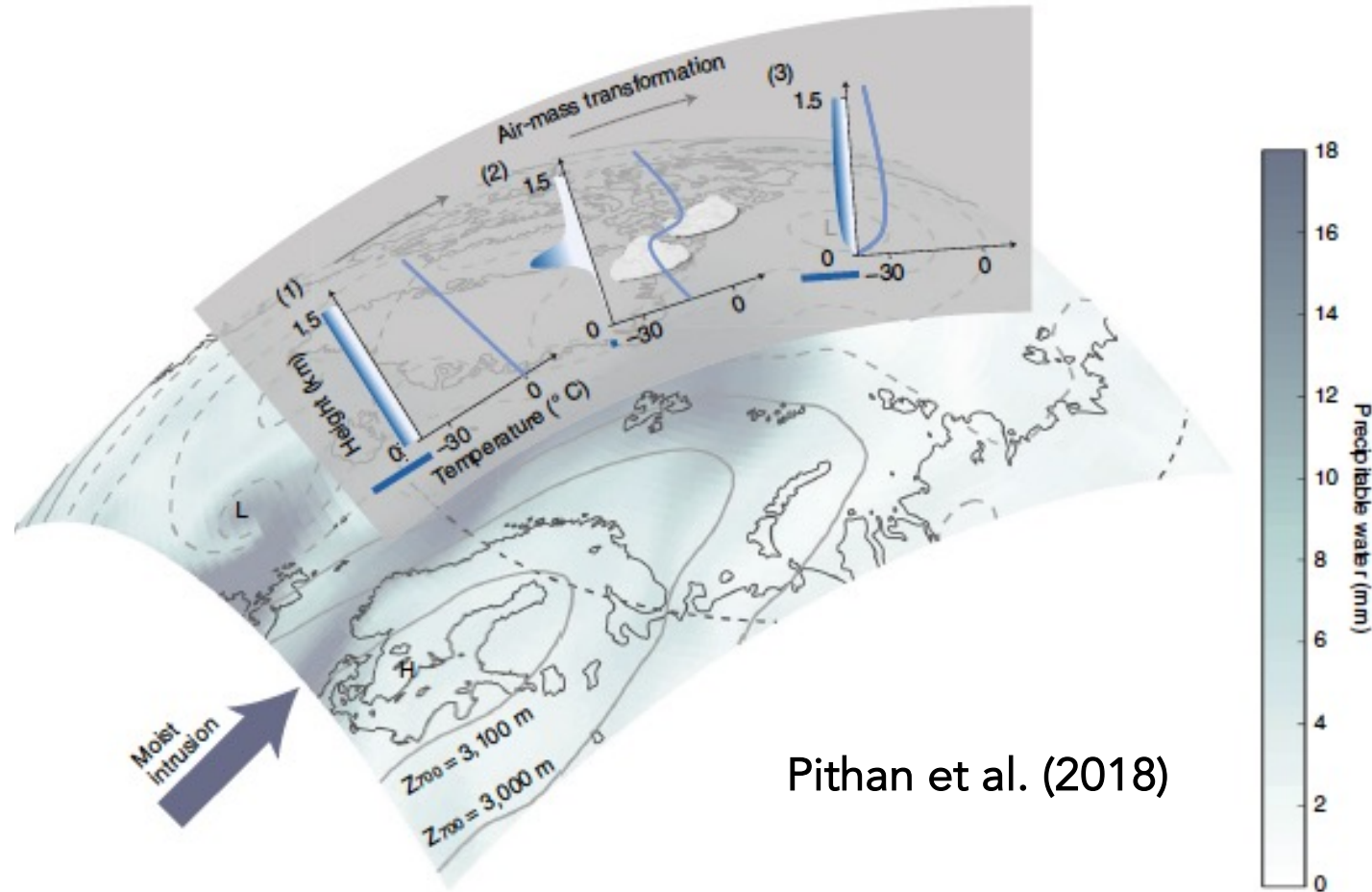
Cardinale and Rose (2022)



Number of high efficiency transport events are increasing at the expense of low efficiency events.

Influence of the air-mass transformation process

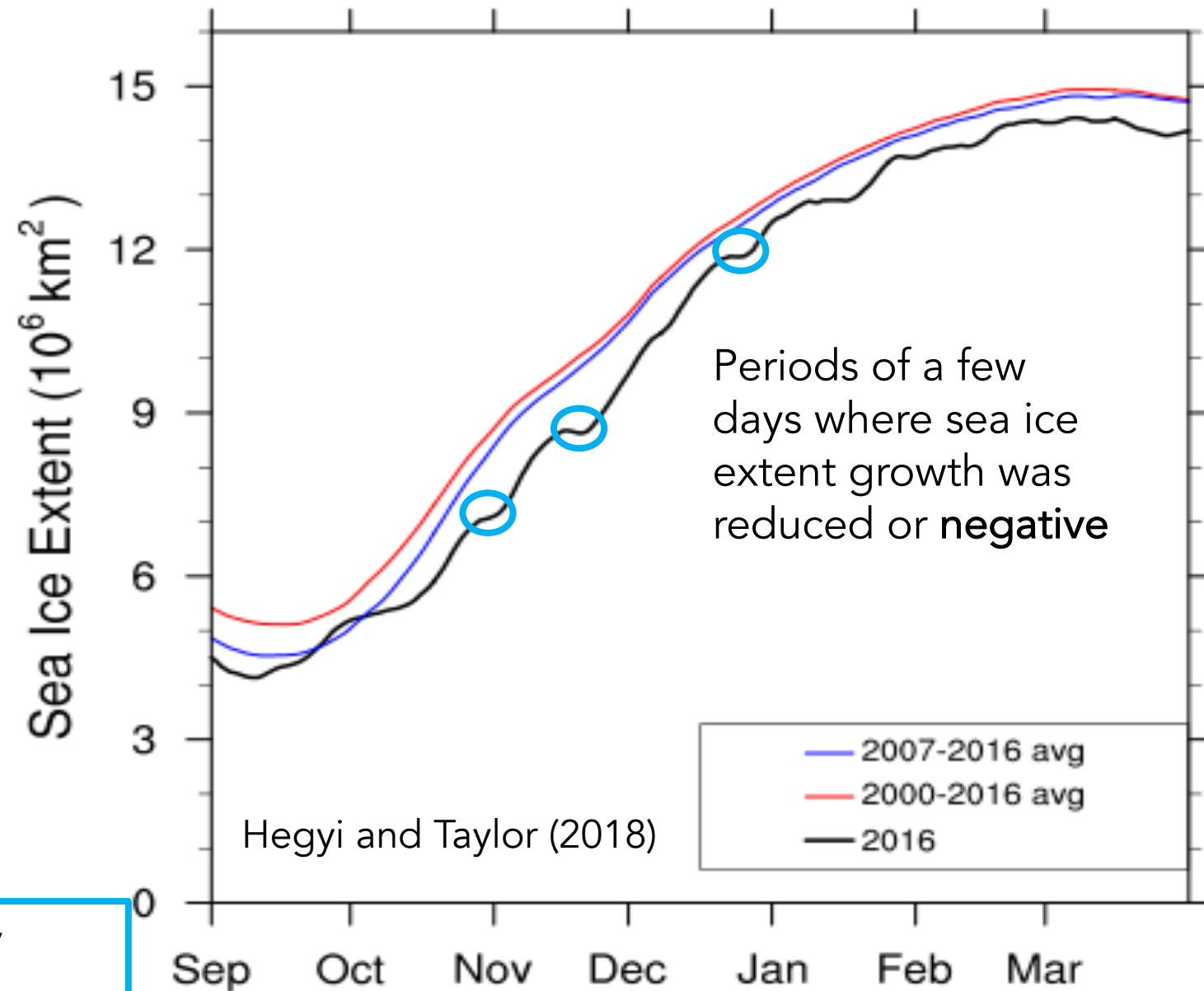
- Moisture intrusions bring warm moist airmasses into the Arctic, that over time transform into more Arctic airmasses.
- This process corresponds to two different atmospheric states (cloudy and radiatively balanced, clear and strong radiative cooling).
- Episodic variability influence AA through:
 - Changes in the frequency of radiatively clear and cloudy states influencing the SEB and cloud feedback.
 - Changes in the properties of the incoming air masses could influence cloud processes
 - Non-linear effects of strongly meridional transports
 - Wind flow regime dependence of surface turbulent fluxes (e.g., off-sea ice vs. on-sea ice flow).



Synoptic to climate times scale: Sea ice as a memory source

2016-17 also exhibited low sea ice extent from October-March, well below recent averages, contributing to one of the lowest end of season Arctic sea ice volume on record.

Sea ice cover is a source of memory enabling the influence of shorter time scales onto climate change time scales.



Common denominator...Memory from sea ice cover

For these synoptic scale processes to rectify onto the larger scale there must be a source of “memory” such that the influences of episodic energy transport events can impact the long-term climate trends.

Impacts on the sea ice cover and specifically thickness is a key source of memory within the Arctic climate.

Heat storage in the upper Arctic Ocean also represents a key source of memory within the Arctic climate.

Recommendations:

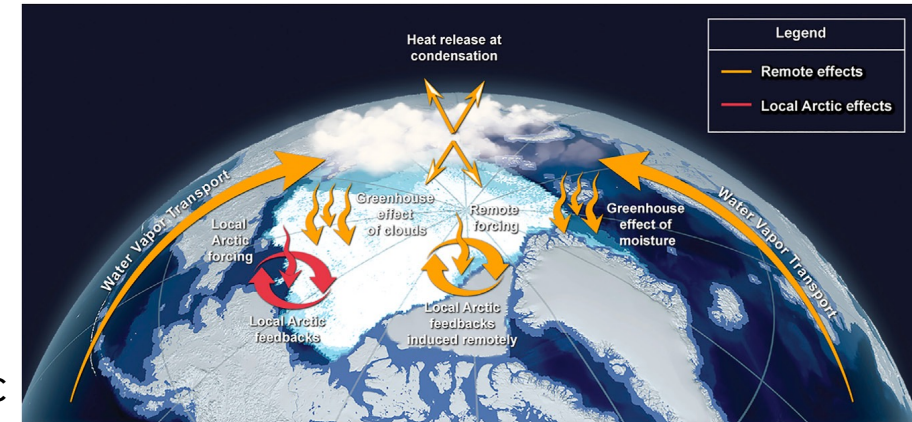
- Maintain and expand Arctic Observing System including both long-term ground-based and satellite observations and Arctic field expeditions. Vision: a permanent, floating Central Arctic Observatory.
- Reduce uncertainties in surface energy budget data: especially from space-based platforms.
- Quantitative understanding of the influence of individual parameterizations on simulations
- climate feedbacks: need model experimental protocols
- Coordinated intercomparison of surface turbulent fluxes and parameterization across contemporary climate models.
- A WCRP-like working group to rethink/redesign Arctic/Polar climate feedback diagnostic techniques.
- Research Foci:
 - Quantify how local feedback and remote process interactions influence the sea ice annual cycle.
 - Quantified understanding of how episodic heat and moisture transport events rectify onto climate change time scales.
- Model intercomparison of the synoptic scale heat transport events
- Field campaign to resolve the seasonal evolution of the ocean mixed layer depth in the vicinity of the MIZ

Conclusion

- Our understanding of Arctic Amplification has evolved substantially over the last 100 years from a single-process phenomenon to one now known to be a coupled atmosphere-sea ice-ocean process.
- The highly-coupled nature of the Arctic, the diverse surface properties, and the harsh conditions have presented humanity a great challenge to understand this fascinating region of Earth.
- We have learned a lot and have a lot to learn.
- One thing we know for sure is that the fate of this relatively small part of planet Earth has far outsized impacts on the society.
- An important step remains, we must raise the Arctic Amplification to a higher place on the climate science priority list to ensure that the surprises that the climate system has in store for us don't have unmanageable consequences.

Remote Processes: Water vapor triple effect

- **Remote-induced warming**—any warming due to a non-Arctic change.
 - Warming resulting from changes in poleward heat transport .
 - Warming due to local feedbacks initiated remote effects are included, since local feedback are not actually local in nature.
- A range of studies show the that between 50 and 85% of the Arctic warming is due to remote processes.
- However, some studies argued that remote process cannot drive Arctic Amplification due to the weak changes or decreases in total heat transport due to the opposing response of SH vs. LH transports.
- Discrepancies between these studies are likely due to
 - The water vapor triple effect
 - Differing attribution of warming to local and remote processes
 - A focus on vertically integrated energy transport.
- **Water Vapor Triple Effect:**
 - The multiple influences of water vapor on the Arctic energy budget from condensation and greenhouse effects of moisture and clouds.
 - Graversen and Burtu (2016) found an order of magnitude larger warming per unit of energy due to the Arctic LH transport than DSE , due to the accompanying changes in specific humidity and clouds.
 - Thus, vertically integrated measures of PHT do not measure this full effect of dynamics.

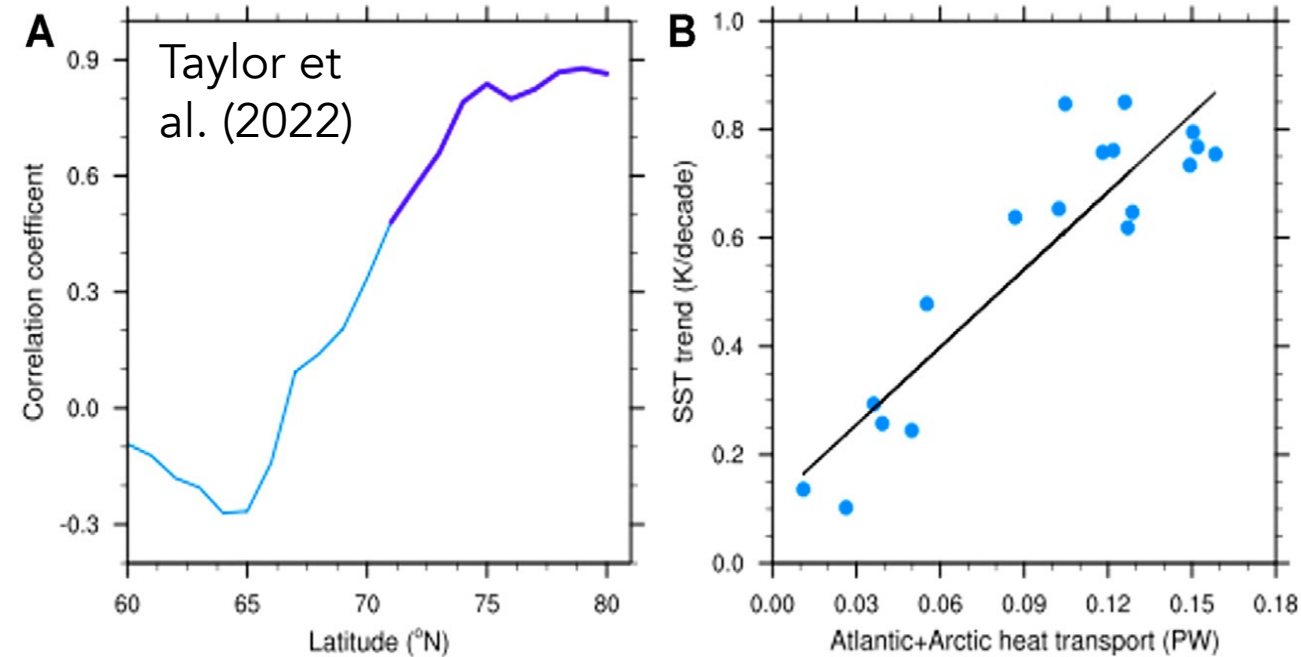


Important notes:

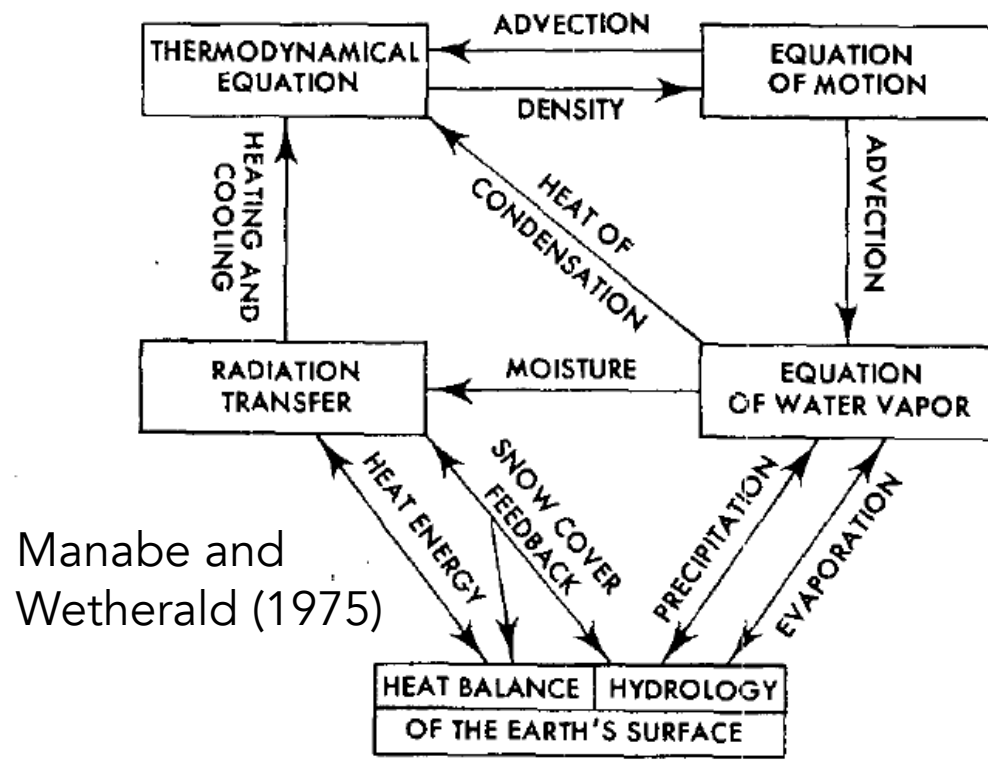
- Studies show that Low latitude warming is efficiently communicated to high latitudes, but high latitude warming is not efficiently communicated to lower latitudes.
- Teleconnections are important to consider and represent in models to capture the “efficient communication” of low-latitude warming to high latitudes.

Ocean Energy Transport Effects

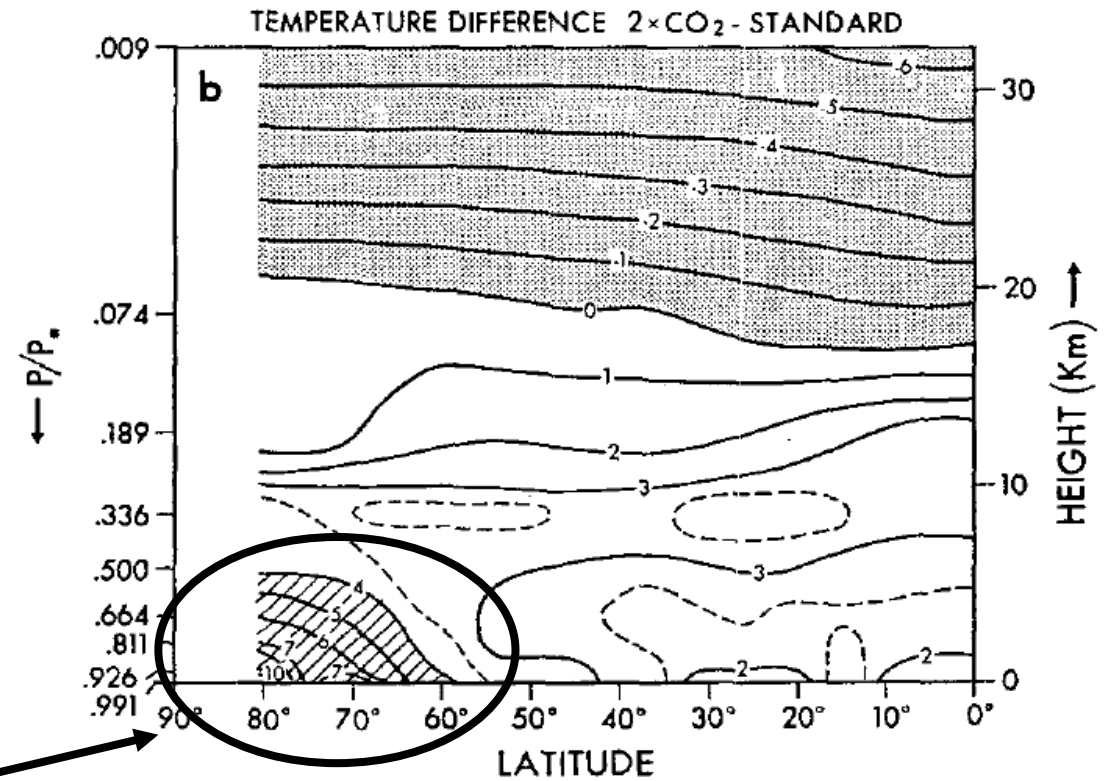
- Changes in ocean heat transport influences Arctic climate by influence surface temperature and sea ice distribution and properties.
- Observations suggest that poleward transport has increased through the Fram Strait and Barents Sea in recent years and climate models also simulate increased poleward OHT.
- Ocean heat transport changes are thought to contribute to additional Arctic warming, however studies offer conflicting interpretations mainly due to the latitude band considered.
- Several mechanisms contribute to enhanced poleward OHT
 - Warmer Atlantic water results in greater OHT with the same mass transport.
 - Ocean circulation changes—e.g., a strengthened North Atlantic subpolar gyre causes increased OHT into the Barents sea decreasing sea ice and increasing oceanic heat release.
 - Studies suggest that feedbacks between the atmosphere and ocean can further enhance this heat transport.
 - Role of the AMOC is debated—a stronger weakening is linked to less Arctic warming. AMOC may be influenced/weakened by the melting sea ice.
- Panel (b) shows that OHT into the Arctic from the Atlantic correlates with projected Arctic warming, such that larger transport increases yields larger warming.



Applying a General Circulation Model to Arctic Amplification



Manabe and Wetherald (1975)



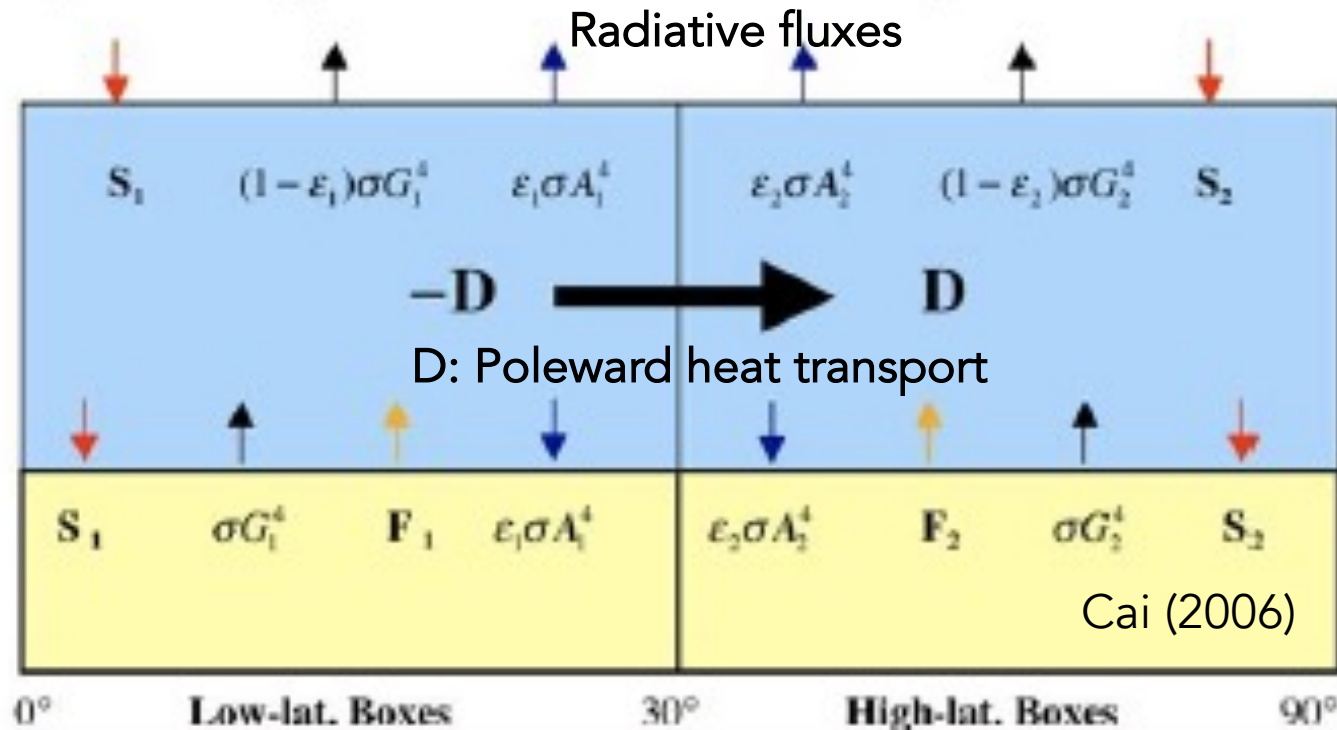
Key Results:

- Surface-based vertical structure of Arctic Amplification.
- Found a compensation between the increased latent heat and decreased poleward sensible heat transport resulting in a near-zero change in the total atmosphere poleward heat transport.

Advanced EBMs: Inclusion of horizontal heat transport

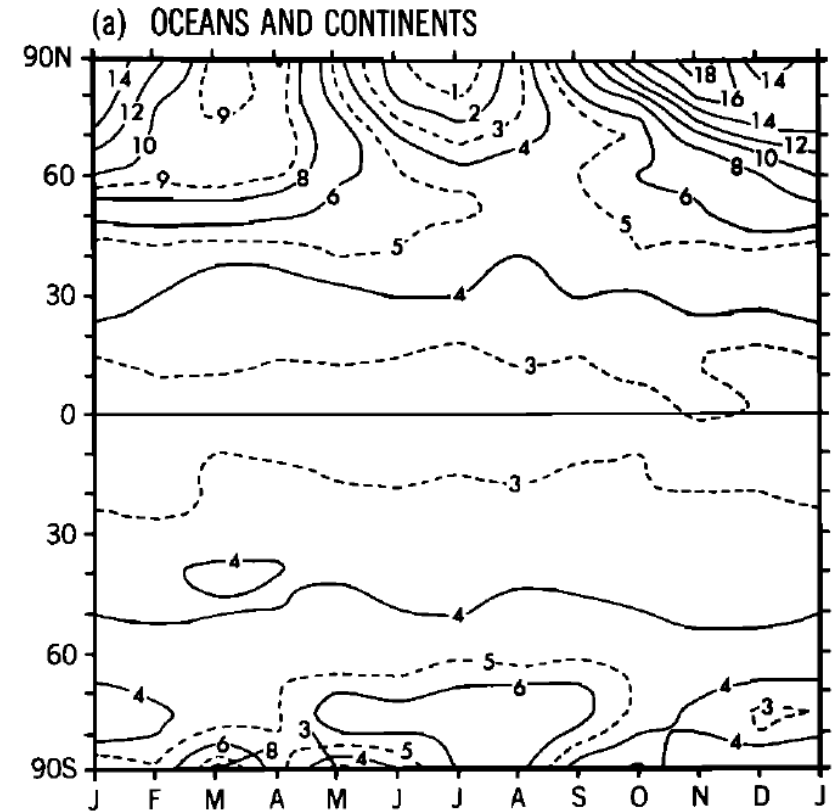
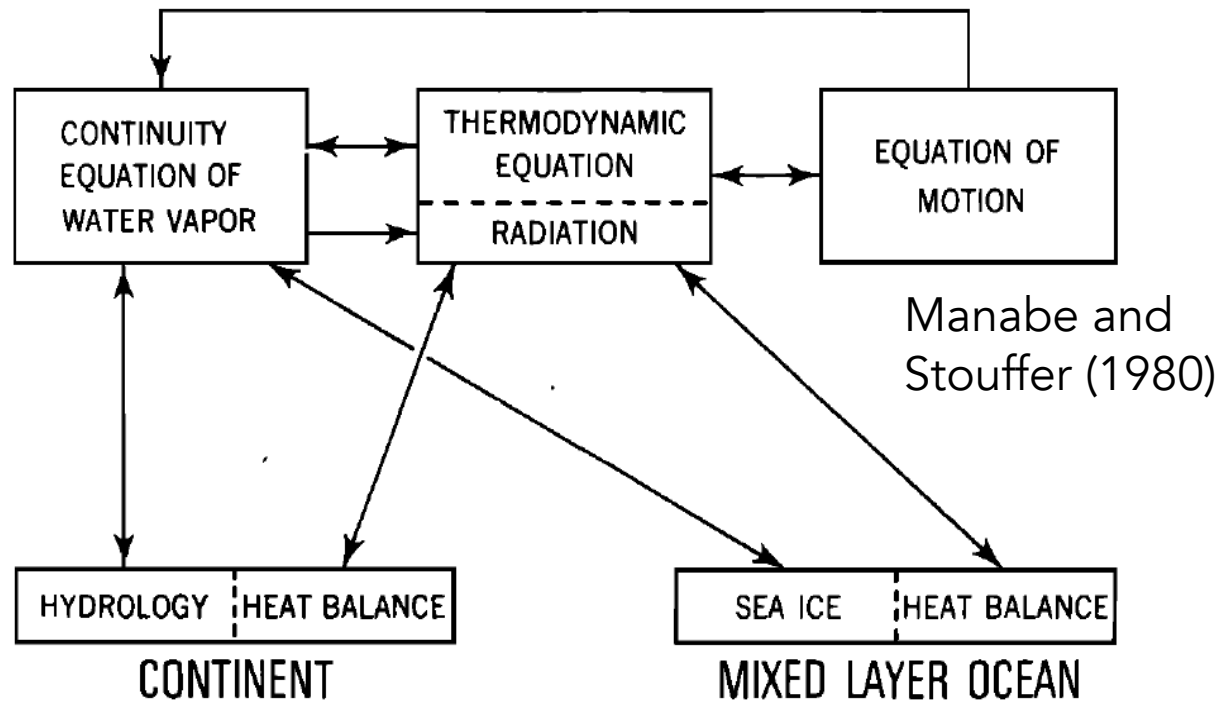
- Sellers (1969) provides an example:
- Horizontal heat transport is included in a zonally-averaged EBM as a horizontal diffusion proportional to the meridional temperature gradient.
- Sellers (1969) found that the Arctic surface temperature and response are very sensitive to the representation of poleward heat transport.

A coupled Atmosphere-Surface Radiative-Transportive Climate Model



- It became clear that to understand Arctic Amplification, poleward heat transport should be resolved to understand the role of the mean circulation and eddies.

A modern explanation for Arctic Amplification: seasonal energy transfer



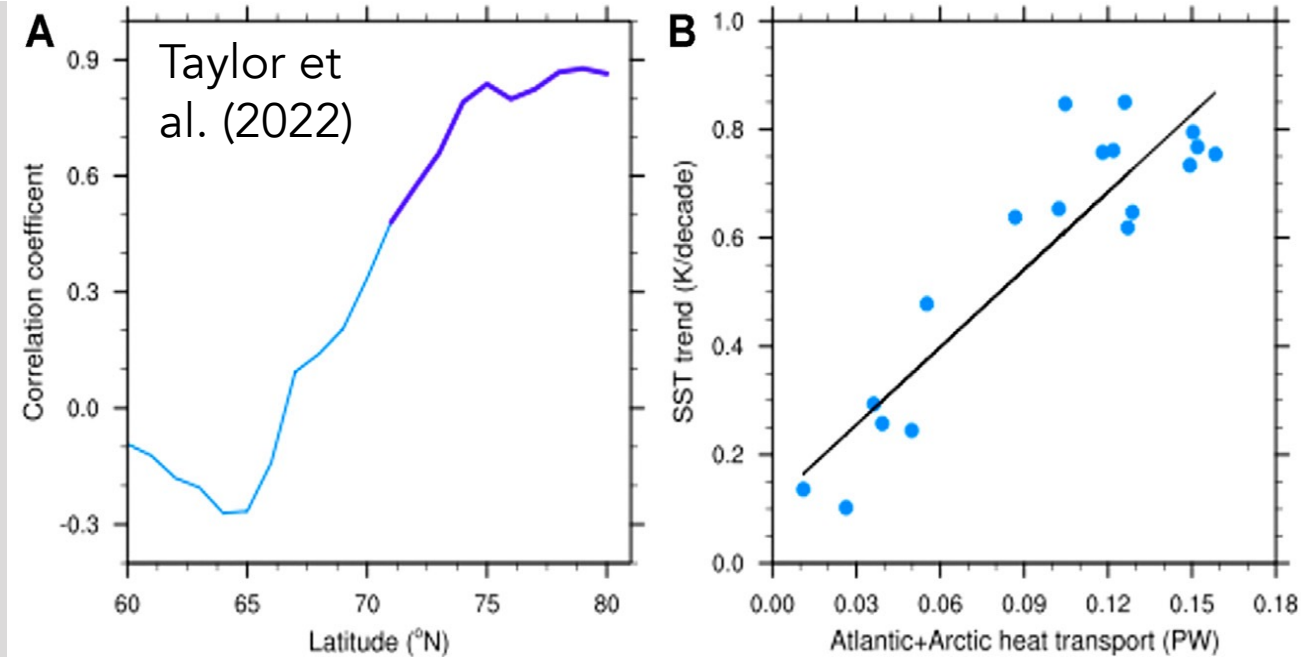
- First study using a GCM with an ocean mixed layer, enabling an annual cycle of solar insolation. No poleward ocean heat transport.
- Key Results:
 - Fall/winter warming maximum and weak warming in summer.
 - Seasonality due to the summer-to-fall energy transfer by ocean heat storage.

MS1980 explanation: Modern Foundation

- The key ideas written by MS80 remain the foundation of AA theory.
- Key Ideas:
 - Surface albedo feedback due to reduced sea ice cover drives increased absorption of sunlight during summer.
 - Extra energy does not cause substantial summer warming due to the large heat capacity of the ocean mixed layer and melting ice.
 - Energy accumulated and stored in the Arctic Ocean surface during summer delays fall sea ice freeze-up and thinner sea ice, increasing surface turbulent fluxes and conductive heat flux
 - Leading to enhanced lower tropospheric warming in fall and winter with a bottom-heavy profile, further enhanced by stable stratification confining warming to near-surface layers.
 - Seasonality attributed to the seasonal energy transfer.

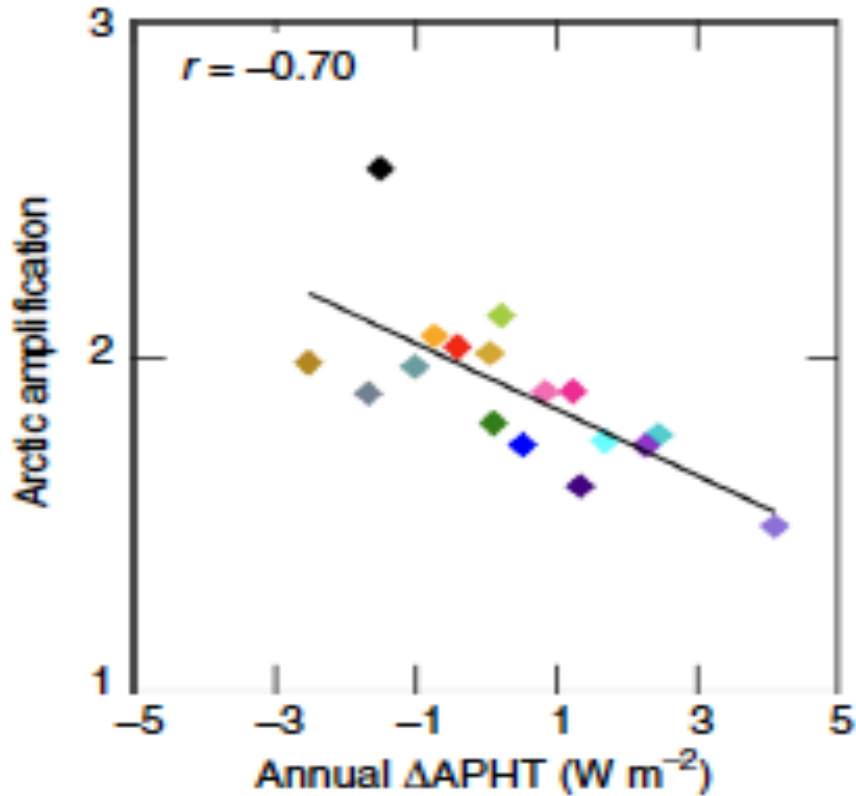
Ocean Energy Transport Effects

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- Several mechanisms contribute to enhanced poleward OHT
 - Warmer Atlantic water results in greater OHT with the same mass transport.
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Cross-scale interactions: Synoptic to climate scale



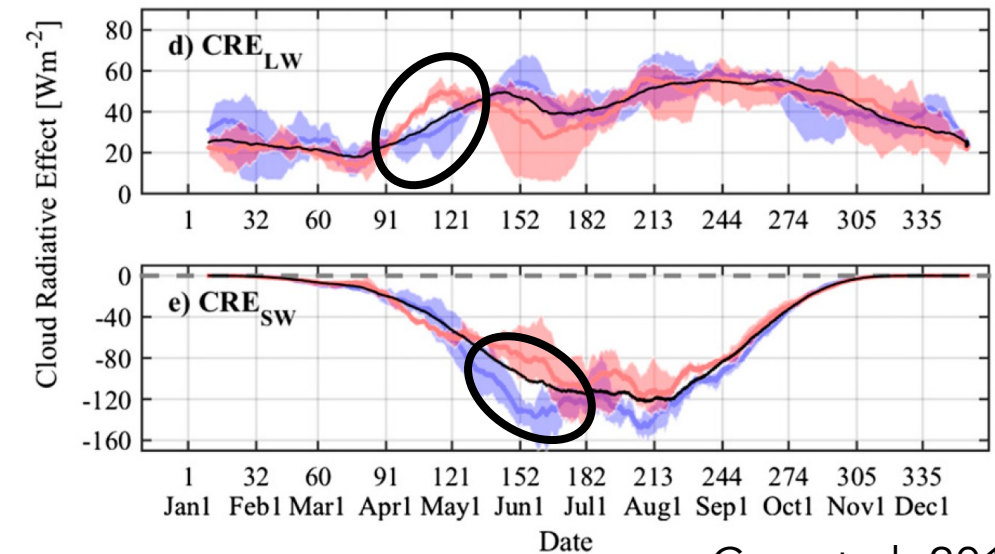
Boeke and Taylor (2018) and others (e.g., Pithan and Mauritsen 2014) find a negative correlation between Arctic warming and atmospheric poleward heat transport.

Two Key Concepts:

1. Different sensitivity of the surface energy budget to the transport of moisture into the Arctic than to the transport of DSE.
2. Sensitivity of surface warming to the vertical structure of the poleward energy transfer

Spring cloud sea ice interactions influence fall sea ice and long-term arctic climate change: local scale surface-atmosphere coupling yielding a long-term response

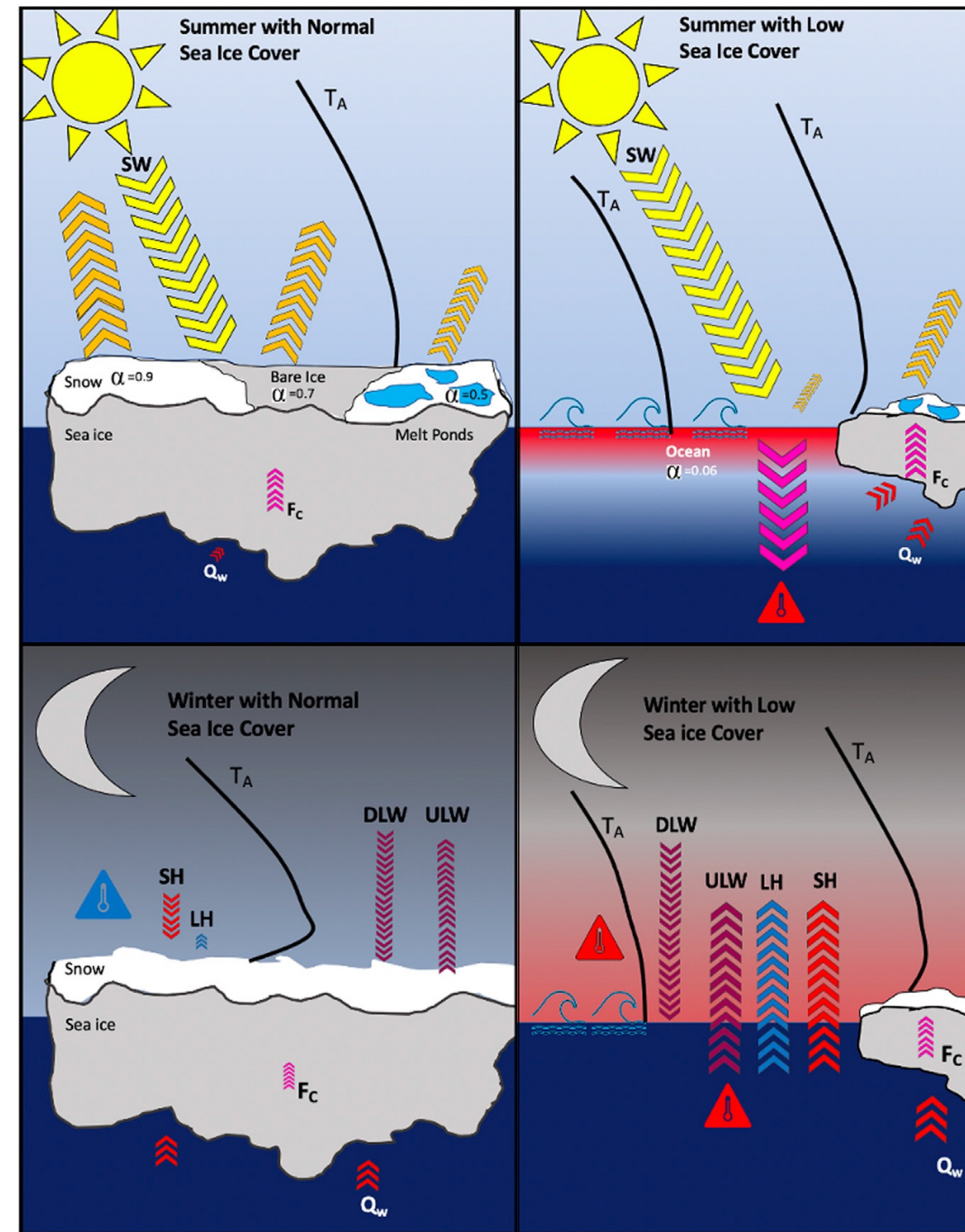
Enhanced Arctic spring clouds driven by local energy transport events=> slow fall sea ice freeze-up and slow winter growth=> yielding a thinner Arctic sea ice cover => more vulnerable to greater summer melt



Cox et al. 2016

Cross-interface interactions

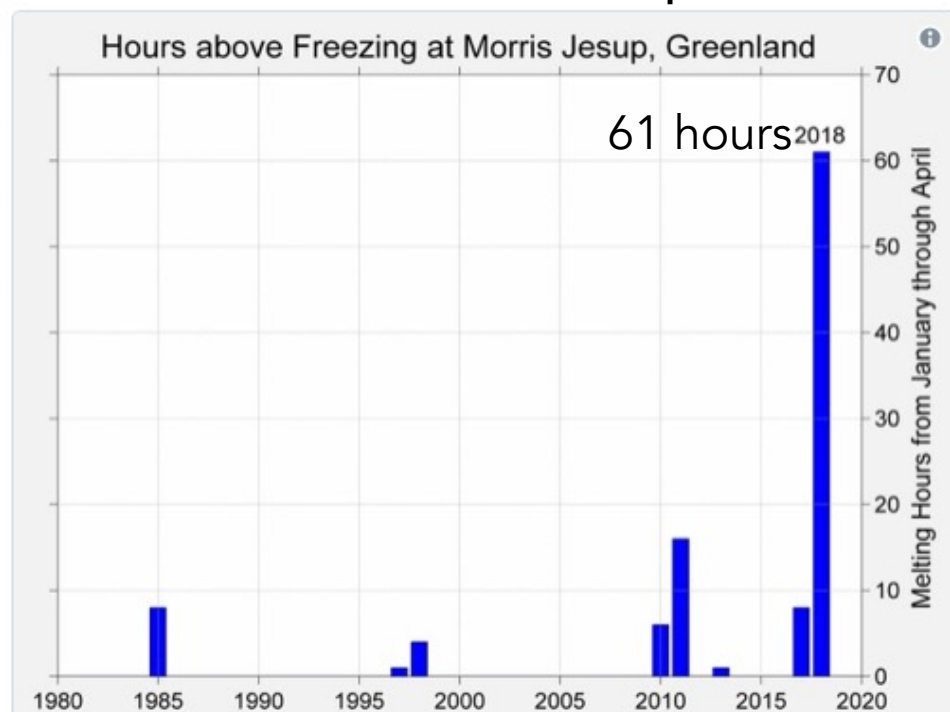
- Sea ice and snow feedbacks:
 - Surface albedo—sea ice and snow cover reductions in response to warming decrease in surface albedo and increased solar absorption, an **amplifying feedback**.
 - Sea ice insulation—warms and/or moistens atmosphere
 - sea ice reductions facilitate increased turbulent energy exchanges (sensible and latent heat) from the Arctic ocean to the atmosphere.
 - Thinner sea ice facilitates a great conductance of heat from ocean-to-atmosphere through sea ice.
- **Key uncertain and unresolved processes:**
 - Sea ice and snow albedo—continuously evolve due to variability in sea ice and snow coverage, thickness, melt ponds, floe size, and topography. These processes are incompletely understood and climate model parameterizations are poorly constrained by data.
 - Dependence between sea ice cover, thermodynamic structure, and clouds.
 - Mechanical sea ice break-up—Less sea ice cover promotes more ocean wave leading to sea ice break-up
- **Key Need: Accurate data of sea ice and snow properties with surface energy budget fluxes under a range of conditions.**



Remote process and local feedback interactions:

Rectification of the synoptic scale onto the climate scale
through sea ice

Poleward heat transport event



 **Robert Rohde**
@rarohde

Replying to @rarohde

In 2018, there have already been 61 hours above freezing at Cape Morris Jesup, Greenland.

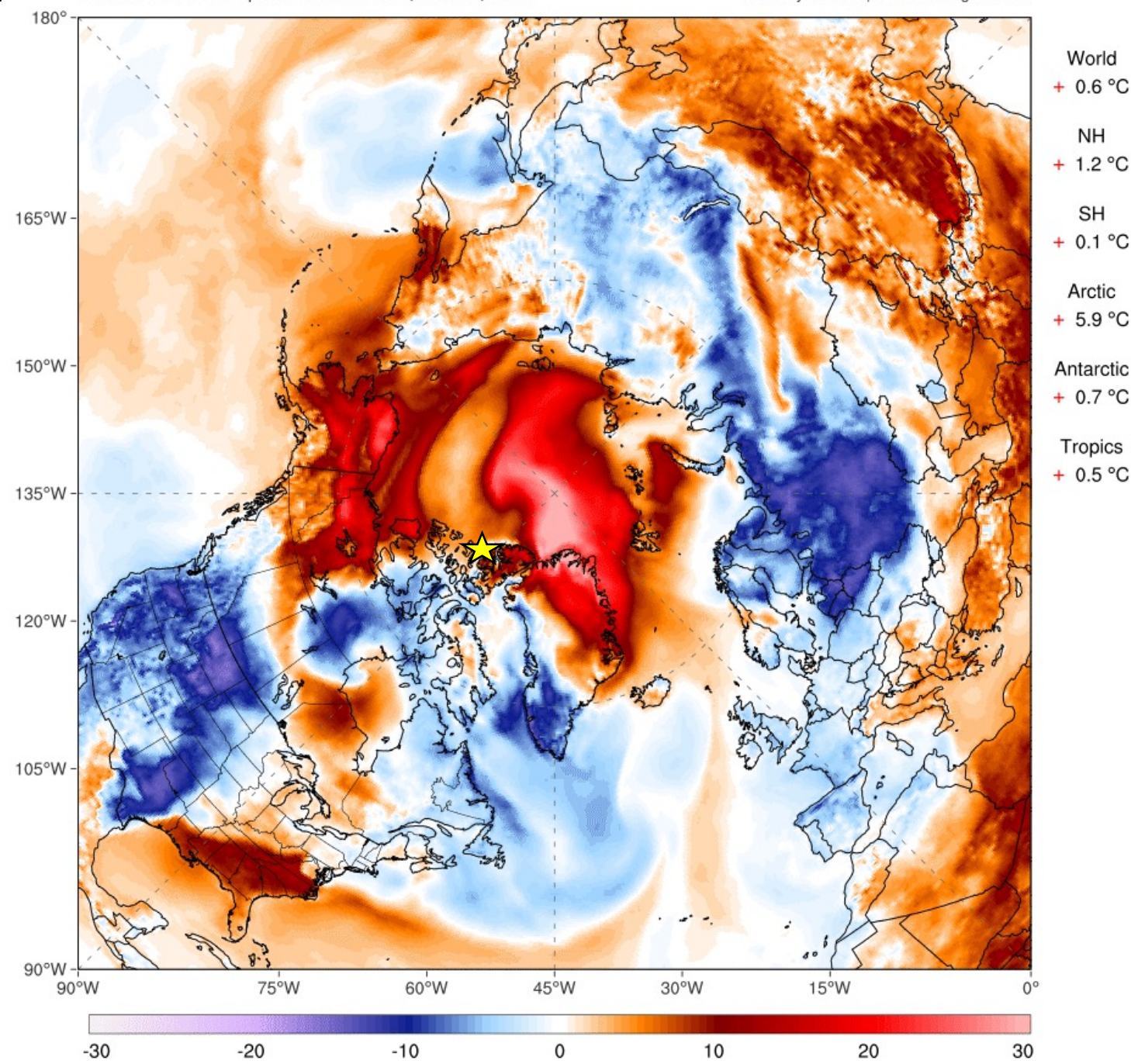
The previous record was 16 hours before the end of April in 2011.

8:02 PM - Feb 25, 2018

♡ 157 💬 180 people are talking about this

GFS/CFSR 2m T Anomaly (°C) [1979-2000 base]
Init 2018/02/23 00Z | f000 Valid Fri 00Z, Feb 23, 2018

ClimateReanalyzer.org
University of Maine | Climate Change Institute



Source: <https://www.theweathernetwork.com/>